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TREND OF OPTOELECTRONICS TECHNOLOGY

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SCIENCE & TECHNOLOGY
JAPAN

TREND OF OPTOELECTRONICS TECHNOLOGY

926C1015 Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp i-565

[Selections from "Trends of Optoelectronic Technology, Survey Report VII—Trends and Perspectives of Optoelectric Technology R&D," published by the Optoelectronics Industry Technology Association. For related report, see JPRS-JST-92-026-L, 9 Apr 92.]

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Preface

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[Text] March 1991
Chairman Koji Kobayashi, Hikari Sangyo Gijutsu Shinko Kyokai

Optoelectronics technology, part of the cutting-edge technology, is spreading deeper into application fields. Total annual production of the optoelectronics industry has surpassed ¥3 trillion at last, growing at the rapid pace of trebling over the four years since it reached ¥1 trillion in FY86.

The element technology of optoelectronics is making further progress thanks to semiconductor technology and microelectronics based on commercial use of semiconductor lasers and optical fibers. Optoelectronics technology is increasingly used in various fields, such as optical communications, information processing, and energy, and its fusion with related sectors like "mechatronics" and biochemistry is expected to further develop. However, there are still many technological hurdles on the way to the real age of optoelectronics.

Under these circumstances, we believe it is significant to continue to study the trend of optoelectronics technology and issue a report on it. With subsidies from the Japan Bicycle Racing Promotion Association since FY80, we have entrusted the study to people well versed in optoelectronics who formed an optoelectronics trend research committee.

As in the previous fiscal year, we asked the committee to study the trend by dividing optoelectronics technology into three sectors: optical communications, optical information processing, and photoenergy. We also asked it to study the future outlook and new materials encouraging the development of optoelectronics technology. For this fiscal year, the committee took up optical recording materials.

This report was made possible with the cooperation of those who take leadership on the front line in research and development in their respective fields, based on research and discussions by Chairman Sueda and 26 other committee members, as well as support from relevant government agencies and companies both at home and abroad. We express our gratitude to them.

FY90 Research Committee

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[Text] **Optoelectronics Technology Trend Research Committee for FY90**

List of Members

Chairman	Tadashi Sueda	Professor, Electric Engineering Department, Faculty of Basic Engineering, University of Osaka
First Subcommittee Manager		
	Takeshi Ito	Chief researcher, Optical Communications Research Department, NTT Transmission System Laboratory, Nippon Telegraph and Telephone Corp.
Second Subcommittee Manager		
	Toshio Honda	Assistant professor, Image Information Engineering Laboratory, Faculty of Engineering, Tokyo Institute of Technology
Third Subcommittee Manager		
	Koichi Tooda	Chief researcher, Semiconductor Engineering Laboratory, Institute of Physical and Chemical Research
Fourth Subcommittee Manager		
	Tetsuro Moriya	Manager, Optical Materials Research Department, Electronics Technology Institute, Agency of Industrial Science and Technology, MITI
Members		
	Fujiro Iwata	Chief researcher, Basic Research Center, Research Institute, Topman Printing Co.
	Yutaka Uematsu	Chief, Technology Management Section, Research Institute, Toshiba Corp.
	Hiroshi Oki	Manager, Optoelectronics Research Department, Research Institute, Sony Corp.

Katsuhiko Okubo	President, Optoelectronics Research Institute, Furukawa Electric Co.
Hyo Kasai	Chief researcher, Applied System Laboratory, Fuji Electric Research Institute
Makoto Kikuchi	Professor, Medical Electronics, Defense Medical Academy
Yoshio Kishimoto	Chief, Physical Science Laboratory No. 8, Central Institute, Matsushita Electric Industrial Co.
Taneaki Kimura	Chief, Optical Development Center, Opto Business Department, Konica Corp.
Kazuaki Sakota	Researcher, Electronic Information Material Institute, Toray, Inc.
Shuji Suzuki	Manager, Network Research Department, C&C System Institute, NEC Corp.
Hidemi Tsuchida	Chief researcher, Optical and Radio System Laboratory, Electronics Technology Institute, Agency of Industrial Science and Technology, MITI
Motoyasu Terao	Chief researcher, Second Department, Central Institute, Hitachi, Ltd.
Haruhiko Nagai	Chief, Second Group of Beam Physics Department, Central Institute, Mitsubishi Electric Corp.
Tatehiko Hidaka	Chief researcher, Optical Information Research Department, Electronics Research Institute, Agency of Industrial Science and Technology, MITI
Yasuhiro Horiike	Professor, Second Category (Electric) of Faculty of Engineering, Hiroshima University
Shigeyoshi Maeda	Chief researcher, Surface Processing Research Center, Second Institute, Nippon Steel Corp.
Minoru Maeda	Deputy manager, Optoelectronics Development Headquarters, Hitachi, Ltd.
Yuichi Matsushima	Chief researcher, Optoelectronics Group Research Institute, Kokusai Denshin Denwa Co.
Kunihiko Washio	Chief engineer, Laser System Business Department, NEC Corp.

Secretariat

Nobu Sato, Hiroshi Kyoya, Yoshiyuki Shimada

Introduction

926C1015C Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp iii–vi

[Text] Today's optoelectronics technology is expected to develop further toward the 21st century as a cutting-edge technology combining optics, electronics, and quantum electronics. The optical industry which is growing smoothly is supported by optoelectronics technology. According to the Optical Industry Trend Research Committee of the association, the Japanese optical industry's output came close to ¥3 trillion in FY90.

For the development of the optical industry, our committee has been studying the trend of optoelectronics. Under a three-year program since FY88, we continuously studied the three sectors of "optical communications technology," "optical information processing technology," and "photoenergy technology" under the theme of "Trend and Outlook of Optoelectronics Technology," and have taken up a topic for each fiscal year.

In concluding the program this fiscal year, we set up four subcommittees with members leading their respective fields and carried out continuous research and studied the outlook. We studied the R&D trend of "optical recording materials" now attracting attention for their future growth potential as the topic for this fiscal year.

Our specific research policies are:

(1) To study the technology trend, dividing optoelectronics technology into three broad areas (optical communications, optical information processing, and photoenergy).

(2) To forecast the progress of optoelectronics, putting special emphasis on future outlook.

(3) To pick up "optical recording materials" as a topic to study this year.

(4) To set up four subcommittees to study the above themes.

(5) To send a research mission abroad and compile a research report.

In line with the above policies, we set up subcommittees consisting of members listed below. The subcommittees conducted research and discussions under managers and the committee discussed reports made by the subcommittees. At the first meeting of the committee, Naoki Ikesawa of the Nomura Research Institute, its key member, delivered a lecture on "the future vision of the optical industry" closely related to the committee. At the second meeting of the committee, the Fourth Subcommittee gave a lecture on "needs of optical recording systems" by Fushiki of Nikkei BP and another on "expectations for new materials and technology in optical recording by Professor Kushida of Osaka University. At the same time, the subcommittee joined discussions at a meeting for the research of the optical disk technology trend held by the Second Working Group of the association's Optical Disk Standardization Committee.

Meetings held:

—Subcommittees—

First Subcommittee (optical communications)
Manager Ito, members Tsuchida, Okubo, Ishiguro, Maeda, Yamaguchi, and Suzuki

Second Subcommittee (optical information processing)
Manager Honda, members Hidaka, Uematsu, Matsushima, Mata, Kimura, and Iwata

Third Subcommittee (photoenergy)
Manager Toyoda, members Washio, Kikuchi, Nagai, Maeda, Kasai, and Horiike

Fourth Subcommittee (optical recording)
Manager Moriya, members Oki, Kishimoto, Sakota, and Terao

—Committees—

First meeting of Optoelectronics Technology Trend Research Committee
Date: 25 June 1990
Lecture: Future Vision of Optical Industry
Naoki Ikesawa, manager, R&D System Laboratory
Technology Strategic Research Department
Nomura Research Institute

Second meeting of Optoelectronics Technology Trend Research Committee
Date: 10 September 1990
Lectures: Needs of Optical Recording Systems
Kaoru Fushiki, editor, Nikkei BP
Expectations for New Materials and Technology in Optical Recording
Koji Kishuki, professor, Physics Department,
Faculty of Physical Science, Osaka University

Third meeting of Optoelectronics Technology Trend Research Committee
Date: 29 October 1990

Fourth meeting of Optoelectronics Technology Trend Research Committee
Date: 4 February 1991

Fifth meeting of Optoelectronics Technology Trend Research Committee
Date: 18 March 1991

We studied overseas optoelectronics technology trends by dispatching a survey mission headed by committee member Honda, who served as manager of the committee's Second Subcommittee, emphasizing optical information processing technology. The places visited are listed in an annexed table. For the results of the research, please refer to "Report on Overseas Survey on Optoelectronics Technology Trends (1990)" issued separately.

This report has been made by compiling the results of research and discussions done by members of research committees. We have to note that parts in particularly specialized subjects of each sector were written by many specialists listed below. We report that the compilation of this document was made possible by the activities of many people concerned and express our gratitude to them.

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March 1991 Tadashi Sueda	Chairman, FY90 Optoelectronics Technology Trend Research Committee

CATV Basic Transmission Technology

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[Text] **(2) Basic Transmission Technology of CATV (Coaxial)**

The most general-use cable television (CATV) system is coaxial-cable CATV.

From the viewpoint of image transmission, the CATV transmission method can be explained as follows: using a coaxial cable as the transmission path and adopting the frequency-division multiplexing (FDM) method under which signals are multiplexed on the frequency axis, all channels of standard television signals are distributed to subscribers by the branching and distribution system while simultaneous microwave amplification is carried out to compensate line attenuation. By changing the reception system of the receiver, it is possible to transmit other signals (such as FM data) by the FDM method.

In CATV, all channels are equally transmitted to all subscribers. In order to provide a special service to a specific subscriber or a number of specific subscribers under special contracts with them, it is necessary to block reception by subscribers who have no such contracts. The scrambling system is used to this end.

Descrambling the scrambled signals is done on the "terminal" side and the CATV administration center remotely controls these terminals to allow or prohibit reception.

Communication is used for terminal control. The mainstay communication between the center and terminals is one-way control from the center to terminals, and two-way communication between the center and terminals is sometimes used. Two-way communication is mostly done by the polling selection method under which the initiative is taken by the center. Contents of such communication are data with a fixed data length (control response, audience rating data, viewing confirmation information, etc.).

Two-way linking of the center and terminals would make various communications possible by expanding the functions of terminals. Various attempts have been made to develop applications similar to videotex, but nothing has yet to be put to practical use.

(3) Position of CATV Network (Coaxial)

A CATV system is a local network. It is possible to interconnect local CATV networks to turn them into a large network, but they are currently operated locally and in this sense CATV networks are local networks.

CATV networks have been connected by linking multiple CATV networks almost in tandem (such as an image distribution network linking a CATV system along the Isukyu railroad in Shizuoka Prefecture and another along the Zumazu-Ito line of the same prefecture). At present, there are 1→n networks as space cable networks using communications satellites.

The size of each CATV network is an area covered by a square roughly measuring 6 km x 6 km (about 3,600 hectares)

(4) Overseas Optical CATV Trend

Table 1.4.1.1 [not reproduced] shows the status quo of optical CATV systems in major countries. Nationwise CATV networks are detailed below:

(a) France

Communication and broadcasting facilities have been installed and operated by state, but the rules have been relaxed and after an experiment in Biarritz (picture + phone), Plan Cable was launched. The program called for setting up an optical CATV network (OG network) as a government organization (GT) partially using private-sector capital with broadcasting carried out by a government-private entity including local governments. However, the spread of CATV was delayed sharply because only optical CATV systems were eligible for government subsidies as those set up under Plan Cable, hindering the project. Currently, coaxial-cable CATV systems are set up under the guidance of Agence Cable. Entities building and managing them include water companies. As of the end of October 1990, about 380,000 families subscribed to CATV.

(b) Britain

The British government hopes CATV will develop as regional communications networks competing with common carriers like BT and MCL. Against this background, the CATV network and total communications network structures must be capable of easy overlaying. Therefore, the service is two-way using a wideband for "down" and a narrowband for "up" communications. Stations are distributed by subdividing telephone station service areas into several parts, making the distance between a station (or kiosk) and a subscriber relatively long. These conditions call for the star network configuration with a selection center (SLC) installed at the center of a service area to select desired channels for transmission to subscribers. This requires the adoption of a large-capacity optical fiber cable, leading to the recommendation of the switched star system (SSS) known as a remote-selection star CATV system. The number of CATV subscribers is small—about 100,000 families as of the end of October 1990.

Measures have been taken since around 1989 to eliminate various restrictions in order to promote the improvement of CATV facilities and investments were invited from foreign corporations as part of the measures. This caused a rapid advance of foreign capital, including U.S. capital, triggering the second CATV franchise rush. American-type coaxial-cable systems are increasing.

With recommendations by the Communications Steering Committee, the government allowed CATV systems to offer regional communication services, including telephone (PS) (CATV in Dockland, London).

BT's subscriber optical system is based on the flexible access system (FAS) under which various signals are optically multiplexed. The Broadband Integrated Distribution Star (BIDS) adopts an active double-star configuration and transmits digital telephone, TV (up to 18 channels), stereo music broadcasting (up to eight channels), and videotex.

The Telephony on Passive Optical Network (TPON) uses a passive double-star configuration to offer telephone and data communication services by digital multiplexing (transmission speed 20 Mb/s, 8 Kb/s, time division multiplexing). BPON is an extended TPON that can also handle image transmission. TPON experiments are under way in Bishop's Stortford, where image services are provided in some parts using TPON.

(c) United States

The United States is the only country where private CATV BSA businesses proved successful. CATV has been using coaxial cables traditionally and the coaxial cable system enjoys high confidence.

The matter of greatest interest for the CATV industry is improvement of picture quality, necessitated by intensified competition due to the diversification of media (completion from VCRs, DBS, and SMATV) and possible competition from high-definition television (HDTV) broadcasting and HDTV-capable VCRs. This stems from the fact that the American CATV industry is entering the maturity phase, shifting from the age of quantity to the age of quality.

As VSB-AM-FDM (SCM) technology entered the practical use stage a study is under way to replace the existing trunk cables with optical fibers to improve picture quality. The U.S. CATV industry is trying to improve picture quality while at the same time improving system reliability.

In-depth talks are also under way on digitizing broadband video signals like TV signals (DigiCipher, Zenith, and other systems). The intentions behind this trend are not totally clear but the move is apparently designed to complement the existing TV system to improve picture quality in the short term and cope with the broadband integrated services digital network (B-ISDN).

Based on the recognition that CATV has become strong enough (competitive) as a medium, there are increasing voices in the United States calling for nurturing B-ISDN as a medium competitive with CATV.

Businesses, centering on telephone companies, are pushing ahead with programs to make subscriber systems optical, called fiber-to-the-home (FTTH) or fiber-to-the-curbs (FTTC) plans. In these projects, image transmission is attracting attention and joint work with CATV operators is done in some parts. Depending on its progress, VSB-AM-FDM (SCM) system technology may influence the FTTH/FTTC technology trend.

(d) (West) Germany

The BIGFON project was launched in 1983 and transmission experiments were conducted as part of it. The country decided to start building CATV networks nationwide from 1984 and DBP is promoting a project which calls for 80 percent of former West Germany to go cable by the market integration of the European Community (EC) in 1992.

CATV networks set up by DBP are coaxial cable networks and about 60 percent had gone cable by January 1990 with subscribers totaling 5.8 million families. Most (about 90 percent) of the subscribers watch programs supplied by the European-version of Space Cable Net.

As part of the BIGFON program, a broadband advance network (VBN) project started in 1986, promoting the replacement of out-of-city networks connecting 29 cities and part of city networks with optical cables.

The BERKOM project is also under way to develop broadband service applications and survey market needs.

DBP is studying how to supply POTS services at low prices to subscribers who do not want broadband services after building optical access lines (OPAL). Raynet's passive bus networks are being tested (in Cologne, Frankfurt, and Lipettal) as OPAL and passive double-star network experiments will be done in Leipzig, Cologne, and Media Park.

DBP will reflect the results of these experiments on the integrated universal broadband network (IFBN) project.

(5) Trend of Optical Image Transmission in Japan

In Japan, CATV started in 1954, the year following the start of TV broadcasting. CATV systems have since been set up and operated chiefly to deal with difficulties in reception.

Licensing of multichannel CATV (so-called city CATV) networks started around 1983 for new CATV services. A network supplying CATV programs using a domestic communications satellite (Space Cable net) was formed in 1989, opening a new age of CATV.

As for multichannel CATV, relatively large-scale systems began to be set up and, in line with that, optical systems started to be used increasingly for trunk lines. For example, LCV (Suwa, Nagano Prefecture) replaced the trunk line with a 900 Mb/s TDM system to improve picture quality on the subscriber end and the system's resistance to thunder.

In the meantime, VSB-AM-FDM transmission technology was put to practical use (at SCAT of Sapporo, Hokkaido, and others).

Japan is leading the world in optical CATV. The installation of Hi-OVIS, an all optical fiber two-way video system, in Higashi-Ikoma, Nara Prefecture, was planned in 1973 and its practical use experiment continued until March 1985. This CATV system was optical down to homes, i.e., Japan led the world in FTTH experiments. Most of the facilities have been taken over by Kintetsu Cable Network (KCN).

Then Nippon Telegraph and Telephone Public Corp. built an experimental model INS system in Tokyo's Mitaka and carried out FTTC experiments. Japan also leads the world in the FTTC area.

IBIS offering market information to businesses is operating in Osaka's Semba district. The system uses a star network of optical fibers to distribute image and provide still/motion picture services on request.

The Tokyo Teleport Center (TTC) plans to improve information and communication infrastructure in Tokyo's seaside subcenter (reclaimed land in Aoumi, Ariake, and Daiba districts). As part of the project, it is promoting FTTH to deliver communication and CATV services to homes with optical fibers. Similar projects are considered for implementation in the Yokohama Minato Mirai 21 area and Osaka Rinku Town.

1.4.2 Status Quo of Optical Image Transmission Technology Applications

(1) SCM

Subcarrier multiplex (SCM) is a method which modulates quantity like the frequency and phase of the electrical system in addition to intensity (amplitude) modulation, using a coherent light source. The generally used method now is the VSB-FDM transmission method, under which electric FDM analog video signals are transmitted after a frequency conversion to the optical level and the original electrical-level FDM signals are obtained in the receiving end after heterodyne conversion.

SCM currently can transmit about 40 channels. As it cannot transmit 60 to 100 channels, one- or two-core fibers are used. As it can convert an existing CATV system's FDM signal columns into optical domain frequencies for transmission and convert them back into very high frequency (VHF) RF signal columns at the receiving end, it is a system that meshes with existing CATV very well. It needs no modulators and demodulators, which require relatively difficult technology, contributing much to reducing the costs of transmitting and receiving terminals.

Many CATV stations consider adopting the SCM system because of this advantage and some are introducing practical systems.

The introduction of the SCM system is aimed at improving picture quality and reliability and giving CATV systems resistance to thunder. Some reports say

the performance of the currently available SCM system is as shown in Table 4.2.1, but others say the number of transmission channels and transmission distance are limited when output is 0 dBm.

The disadvantage of the SCM system is that its power budget is small. Because of this, it is difficult to connect a CATV system's subhead ends with a bus network using optical branches. It is also difficult to make many branches from one light source.

Using an optical fiber amplifier now being put to practical use, it is possible to complement the smallness of the power budget. Distortion and noise characteristics are critical even within the SCM system section alone and the addition of the optical amplification system aggravates the situation, making it necessary to pay attention to standard distribution between the optical and electrical systems.

However, coherent light source performance is expected to improve further and the SCM system will be used more effectively as a system that can send many channels (about 40~50 channels/core) of TV signals at a relatively low cost and high performance over a comparatively long distance, overcoming disadvantages of the coaxial cable system.

The future advance of optical fiber amplifiers will enable the building of active networks or all-passive networks (single/double-star networks), increasing applications in the CATV domain.

In addition to its impact on CATV, the SCM system that can transmit many channels of video information simultaneously may encourage networks to go passive in the future, greatly influencing the structure of networks, such as FTTH and FTTC networks which are subscriber systems of B-ISDN.

The adoption of the SCM system is increasing rapidly (S-CAT of Sapporo and others). An experiment was conducted to turn multiple sub-Nyquist sampling encoding (MUSE)-AM signals into FM waves with a modulation signal band width of 27 MHz, the same as the broadcasting satellite (BS) system, using the SCM system and 31 channels (50 MHz~1.3 GHz) are frequency-multiplexed at the electrical level for transmission.

(2) Others

(a) AM, FM, PFM

In the early stages when optical systems began to be used in CATV and other image transmission sectors, designing took into account transmission after amplitude modulation (AM), frequency modulation (FM), or pulse-frequency modulation (PFM).

In the AM system, it is necessary to prevent mode noise caused by a change in the optical fiber refractive index and a shift in the connection section when light with good coherence passes through MMF. Therefore, about three channels per core have been the limit for transmission over a distance of more than

1 km. To deal with the problem, Japan Broadcasting Corp. (NHK) realized multichannel transmission using MMF with a larger numerical aperture (in Kuriyama Village, Tochigi Prefecture).

FM, PFM, pulse-wavelength modulation (PWM) and pulse-position modulation (PPM) have frequently been used in the transmission of a small number of channels of analog video signals. These modulation methods are also used in many optical experimental systems abroad.

(b) PCM, PCM-TDM

Pulse-code modulation time division multiplexing (PCM-TDM) is technology already established in the telecommunications sector and 900 Mb/s and 1.8 Gb/s systems are also used in the CATV sector as well (transmission between hubs, LCV in Suwa, Nagano Prefecture). They are used for transmission of 10 and 20 channels, respectively, at 90 Mb/s per channel.

As it is a digital transmission system, there is little deterioration in the signal to noise ratio (S/N) ratio). Moreover, its large power budget easily allows the building of a bus network and optical signal distribution to many trunk line systems at a transmission point. On the other hand, a modem is required for each channel, excepting baseband input signals, on the transmitting end and as many modems as the number of transmission channels are needed at the receiving end. Thus, transmission of many channels is costly.

Studio-standard National Television System Committee (NTSC) image transmission PCM systems are used to transmit 150 Mb/s per channel (TTNet, NHK hookup circuit).

(c) FSK, PSK

Coherent optical communications corresponds to optical communications on existing microwaves and millimeter waves, utilizing light's characteristics as waves—frequency and phase—just like electromagnetic waves. Frequency-shift keying (FSK) can directly modulate LD and needs no external modulators, unlike amplitude-shift keying (ASK) and phase-shift keying (PSK), but its uneven FM characteristics have been a problem. However, the advent of the phase-control domain feedback laser diode (DFB-LD) made it possible to obtain uniformity. Since around 1985, communications research institutes in major countries have been actively carrying out experiments on very long-distance optical communications and gigabit transmission was made possible by the differential synchronous phase-shift keying delay detection system and continuous phase FSK (CPFSK) heterodyne delay detection. These technologies are expected to be introduced into the image transmission field un the future.

(d) Optical FDM, WDM

Multiplexing systems peculiar to optical systems are optical frequency-division multiplexing (optical FDM) that multiplexes at gigahertz-order channel intervals and wavelength-division multiplexing (WDM) for multiplexing at nanometer-order channel intervals. Examples of the latter include a

transmission experiment in which HDTV-PCM signals (668.25 Mb/s/ch) were wavelength-multiplexed for 10 channels at 1.9 nm intervals.

1.4.3 Trend of Optical Image Transmission Technology

(1) Analog Image Transmission Technology

The method to transmit analog signals over an optical system is already put to practical use in NTT's image transmission service and CATV.

(a) Technology for Transmitting Over Small Number of Channels

This technology is used for point-to-point image transmission and single-star or double-star networks having a remote channel selection mechanism (SLC) at centers or hubs because transmission over a small number of channels is enough for them. At the transmitting end, signals to be transmitted (such as several channels of TV, several voice broadcasting channels and control signals) are arranged on the frequency axis and undergo intensity modulation (IM) for transmission. A customer-premises device on the receiving end demodulates them to receive desired information on a terminal.

This technology has already been established in optical systems. A larger number of signals can be sent when WDM is also used and it is possible to constitute up and down circuits using a single-core optical cable.

(b) Multichannel Transmission Technology

This is the most commonly used technology for coaxial cable CATV. A large number of signals are arranged on the frequency axis (by FDM) and distributed to the receiving end (each household) as they are. It was difficult to apply this technology to optical systems.

But the debut of near-coherent light sources put to practical use systems similar to FDM transmission in the electronics domain (SCM or VSB-AM-FDM). That is, optical systems began to be built in the optoelectronics domain.

Distributed feedback (DFB) and distributed Bragg reflector (DBR) semiconductor lasers generating a stable single-axis mode beam are used as coherent light sources. Further stabilization of the oscillating frequency is sought and a typical stable-frequency laser is the DFB-multiquantum well (MQW) semiconductor laser. Stability of the DFB semiconductor laser is tens of megahertz, while the frequency of the DFB-MQW semiconductor laser is narrowed to several megahertz.

Such coherent light technology has made possible FDM transmission similar to that in electronics (i.e., SCM). This not only greatly affected the development of optical CATV but also brought a technological innovation to the conventional coaxial cable CATV.

SCM is advantageous in the following points:

(1) As in FDM transmission, VHF signals can be raised to the optical domain only by frequency conversion on the transmitting end, and the receiving end can convert the optical domain signals back into VHF signals through frequency conversion.

(2) SCM thus requires numerous modulators and demodulators.

By using these characteristics, it is possible to further improve conventional coaxial cable CATV technology.

In coaxial cable CATV, broadband simultaneous multiwave amplification is done in order to compensate line attenuation. At the time of amplification, nonlinear distortion is inevitably caused by the amplifier's nonlinearity and white noise is generated. When signals are boosted many times, distortion and noise caused by each amplifier will be cumulated. The performance of the current amplifying element enables transmitting about 30 channels of standard TV signals to a service area measuring about 6 km x 6 km, but further performance improvement is called for. The service area can be expanded, with picture quality improved and the number of channels transmitted increased, by applying SCM to trunk lines. When erbium-doped fiber optical fiber amplifier is used in combination with SCM, new application fields will be developed.

(c) Others

Other methods of analog transmission of video signals include wireless distribution. There are also ground broadcasting and wideband subscriber radio using microwaves, but the signal distribution system using a satellite has factors that will make it a major medium.

Satellite broadcasting is already used commercially and one channel of JSB was offered in November 1990 in addition to two NHK channels, making satellite broadcasting more attractive.

Entrusted broadcasting using a communications satellite will start around the winter of 1992. The broadcasting can supply programs similar to those of CATV to general households and is expected to play an important role as a subscriber system.

(2) Digital Image Transmission Technology

(a) Trend of Digital Image Transmission Technology in Telecommunications

In order to meet diversifying and advancing needs for communications, 64 kb/s N-ISDN services are already offered in Japan and other countries. Demand is increasing for image communications at a higher speed of tens of megabits per second, HDTV image transmission, high-speed file transfer, and communications between local area networks (LANs). B-ISDN is being studied in order to offer high-speed, wideband services including image to meet such demand.

Image services generally handled by communications systems are shown in Table 1.4.3.1 [not reproduced].

When seen from the viewpoint of image transmission, these image information have common characteristics—information generated and its average rate, burst characteristics, and allowed error rate and allowed delay amount and their fluctuation amounts. Information generated and its average rate determine required conditions of the transmission medium's needed bandwidth, the burst characteristics those of multiplexing efficiency, and the allowed error rate and allowed delay amount those of transmission quality.

Basic conditions for considering image transmission technology in telecommunications are that image transmission ranges from terminal-to-terminal transmission/reception as in video phones to simple "distribution" of signals as in TV program distribution, and that the network is a global or national network unlike local networks of CATV.

Various band compression technologies have been proposed based on these image information parameters and conditions. At the end of 1990, the International Telegraph and Telephone Consultative Committee (CCITT) issued its first recommendation based on ATM, approving transmission speeds of up to 150 Mb/s and up to 600 Mb/s and ATM with the SDH frame and full ATM as interface conditions for the user interface network (UNI).

Discrete cosine transform (DCT) is being considered as band compression technology for still images and DCT with motion compensation for motion pictures. For HDTV and other high-definition images, subband coding is seen as a promising technology. One condition of ATM transmission, transmission technology that keeps the transmission rate constant (CBR mode), is also expected to remain.

Image encoding studied so far for teleconferencing and video phones is designed to transmit signals at a bit rate as low as possible by curbing redundancy. But the amount of information generated by images varies widely according to kinds and characteristics of images, and when interframe encoding is used, encoding output fluctuates. If a buffer memory is used to smooth the information amount, the delay time will increase. In either case, part of the information must be discarded (cell discarding) when the information amount reaches a certain level, causing a distribution in picture quality.

In this context, variable-speed encoding (packet video) is attracting attention. When variable-speed encoding is applied to an ATM network, a transmission quality deterioration still occurs due to cell discarding. As image transmission requires real-time capability, no recovery is possible by retransmission protocol as in packet communications. To deal with this problem, hierarchical encoding is under study.

(b) Trend of Digitization in CATV

(i) Digitization of Image Transmission

Digitized image transmission in a CATV system is already used in the trunk line domain. As TDM multiplexing is adopted for it and transmission of many channels requires many demodulators on the transmitting end and modulators at the receiving (reproducing) end, cost problems even in trunk line systems develop. For similar reasons, it is difficult to adopt a digital system (PCM-TDM) CATV's subscriber network section (between hubs and subscribers) as it is.

One idea to avert this problem is to adopt an SLC network and transmit only one to several channels selected at the SLC to subscribers. But this makes the station (or hub)-subscriber system a star network, which is not economical for offering distribution-type image services. The possibility of adopting digital transmission for the subscriber system is thus slim.

As the size of an area covered by the SLC greatly affects cost efficiency of a system, system configurations that will greatly reduce the area are being considered. Systems designed on the basis of this idea include SSS of Britain covering about 200 households (one WSP accommodates about 240 households) and the minihub of the United States (one hub accommodates 16 households). Under these configurations, the need to employ a digital system becomes even smaller. In view of these restrictions in the application stage, it is difficult to adopt a digital system for the subscriber system of an image distribution network, if not for other narrowband ISD services.

(ii) Digitization Matching Communication Services

Much is expected of the use of the two-way function of CATV as part of diversifying use of CATV. But most applications of the two-way function are those accompanying CATV services, such as CATV program selection, payment information collection and monitoring system operation. Some CATV systems have recently been conducting experiments on center-end services like automatic power and water meter checking and central monitoring of security systems at security service companies as well as end-to-end (communication) services like personal computer communications and wired telephone. But these are either low-speed data communication services using modems or analog telephone services. Meanwhile, the CATV Infrastructure Technology Research Institute is conducting research on using CATV as the subscriber company access system and supporting ISDN basic interface (2 x 64 kilobits per second + 16 kbps) to realize end-to-end digital communications services.

The CATV Infrastructure Technology Research Institute is an institute set up in March 1988 with funds provided by the Infrastructure Technology Research Promotion Center. It is conducting "tests and research on digital integrated communications technology in a CATV network," a project that runs four years and seven months until September 1992.

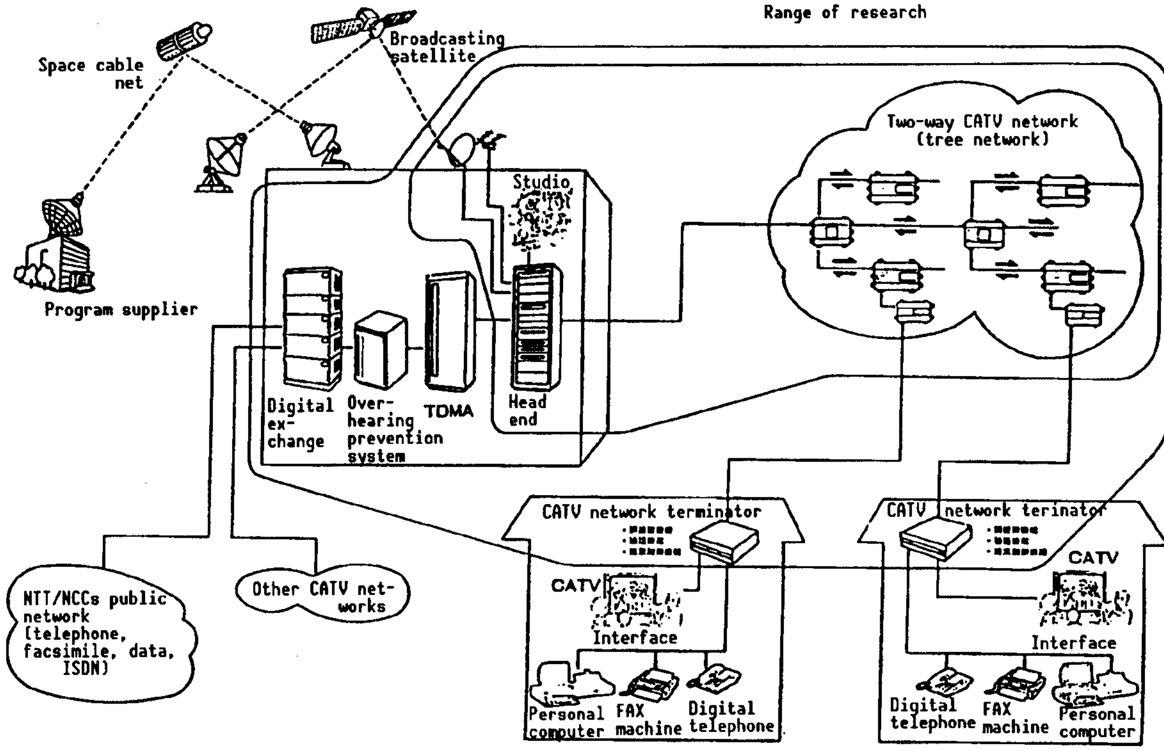

Figure 1.4.3.1. Total System Concept

Figure 1.4.3.1 shows a system concept studied by the institute.

This digital integrated communications system enables ISDN communications services by adding time-division multiplexed access equipment, ISDN-capable digital exchanges, equipment preventing overhearing, CATV network terminating equipment (NTc), and ISDN terminals to a tree-type two-way CATV system now spreading.

The time-division multiple access (TDMA) system is used as a system to transmit digital signals over the CATV network. Up and down TV channels are allotted for TDMA signal transmission on a frequency-division multiplex (FDM) transmission path to which a 6 MHz band is assigned to each TV channel, and digital signals modulated by quaternary phase-shift keying (QPSK) are transmitted.

Down transmission is done after QPSK-modulating time-division multiplexed signals and they are extracted by an allotted time slot at each NTc. As for up terminals, QPSK-modulated burst signals are sent out from each NTc. At this time, send-out timing is controlled with precision of 1/16 of one symbol to prevent a collision of burst signals. At the same time, it becomes possible to improve multiplexing efficiency by eliminating preamble signals usually necessary for burst signal transmission. This method is called high-precision delay-measured control TDMA.

As the subscriber access system uses TDMA on the CATV network, the ISDN digital exchange for this system is a demand access exchange control type. This improves time slot usage efficiency.

Due to exchange control, TDMA control, overhearing prevention control, and ISDN basic interface support, the CATV network signal transmission frame format is as shown in Figure 1.4.3.2.

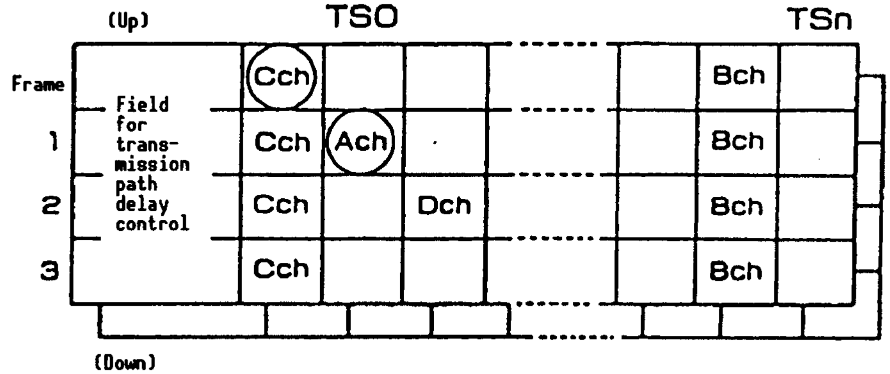

Figure 1.4.3.2. Example of HDTV Encoding

Considering standardization, use of ISDN terminals and interconnection with outside networks, this research assumes Channel B as 64 kHz. The frame format also takes substrates (32, 16 kHz) into account.

Because of the tree structure of the CATV network, down transmission signals are conveyed to all NTcs. The exchange's demand assignment control allows only one NTc to extract signals, but someone with advanced technology may be able to eavesdrop. Thus, a device to prevent overhearing is necessary. The system's cryptographic key delivery management system adopts the public key system and high security is obtained by discarding the NTc's cryptographic key every time a call is made. As the system handles both voice and data in an integrated manner, the cryptograph algorithm employs a method that minimizes a processing delay to prevent influence of voice echo.

NTcs are installed at subscriber homes and have functions to counter the exchange, overhearing prevention equipment, and TDMA system installed at the center and make the tree-structure CATV network virtually a star network. The user interface is the ISDN basic interface (2B + D) and ordinary ISDN terminals can be used as they are.

Optical analog transmission using VSB-AM direct optical modulation has recently been put to use in CATV systems. This digital integrated communications system can be used if the transmission path employs frequency multiplexing.

What is important in using the two-way function of CATV is how to cope with the flow-in noise. The adoption of the optical system for CATV is effective in reducing jump-in noise in the trunk like section.

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(3) Coping With Higher Picture Quality

(a) Supporting Conventional Transmission System

(i) Higher Performance of Amplifying Devices

An amplifying device with high enough secondary and tertiary distortion and NF characteristics is needed for a system that compensates line attenuation by simultaneous multiwave amplification like CATV in order to transmit images while maintaining high picture quality. It will become necessary either to bring the current hybrid integrated circuit (IC) to the monolithic IC level or use gallium arsenide (GaAs) field effect transistor (FETs) for millimeter-wave integrated circuit (MMIC).

(ii) Complementing Analog Transmission System

The largest problem of the conventional analog transmission system is the minimization of the amplifying device's distortion and noise. The next best way is to minimize the number of amplifier cascade connection stages. To this end, it is necessary to use a transmission line with a small transmission loss. In the early days, optical fiber cables were used to achieve the latter (such as Nippon Telegraph and Telephone (NTT) image transmission services and CATV tie lines.).

It is known that the cost usually increases rapidly as the adoption of the optical system comes closer to subscribers.

When a compromise is made between the minimization of the number of amplifier cascade connection stages and cost, it is a realistic approach to use the electric system for sections close to subscribers and the optical system for sections close to the center (or hub) (like FTTC).

Based on this idea, replacing coaxial cable trunk lines with optical fiber cables was proposed in the wake of the debut of the SCM method using a DFB laser (the protected fiber system, fiber backbone system, fiber trunk, feeder system, etc.).

Another analog transmission complementing method is the SLC image transmission system. The system, based on the FDM system, is designed to lower the highest transmission frequency by reducing the number of image channels transmitted for long-distance transmission by decreasing transmission loss (the Dial-A-Program system of Britain's Ready Fusion and the switched star system based on it).

(iii) SLC FM Transmission

This is one of the ways to complement the analog transmission system. FM-FDM transmission of video signals (multiple) is proposed to take advantage of the characteristics of the FM modulation system that it is resistant against nonlinear distortion and thermal noise.

As FM signals have a wide occupied bandwidth (27 MHz/channel for the satellite system), it is not possible to send all channels by FM-FDM. This leads to an idea that SLC FM transmission is suitable.

Satellite broadcasting, broadcasting using a communications satellite and MUSE-FM of Hi-Vision broadcasting are expected to become compatible. Taking this into account, SLC FM transmission (demand access type) could become a promising system.

(b) Coping With HDTV

(i) Broadcasting CATV

HDTV distribution systems include deterioration by satellite broadcasting. HDTV broadcasting has been conducted one hour per day, using the BS-2 satellite, and HDTV strength broadcasting is going to start, using the BS-3b. The occupied bandwidth is 27 MHz and the modulation method is FM (same as usual satellite broadcasting). Preparations for HDTV broadcasting have been making progress—the multiple subsampling encode (MUSE) decoder has already become an LSI and the marketing of HDTV receivers has been announced.

In line with the past coaxial cable AM-FDM broadcasting, CATV systems plan to transmit HDTV by the MUSE-FM or MUSE-AM system. Under MUSE-AM, one channel of HDTV signals will be transmitted by the vestigial side band (VSB) method on an occupied bandwidth of 12 MHz. As NTSC (standard TV) signals also use VSB, MUSE VSB-AM matches well with them. But CN becomes severe because VSB-AM's transmission occupied bandwidth is large. As group delay at the MUSE sampling frequency is severe, phase equalization is required at the receiving end.

(ii) HDTV Distribution by Communications

HDTV signal distribution using a telecommunications system has long been studied because it has an important bearing on the B-ISDN concept.

The bandwidth needed for HDTV signals is 20 MHz for luminance signals (Y) and 7 MHz for chromatic signals (P_R, P_B) and the digital bit rate is around 600 Mb/s, requiring a very high transmission speed. Therefore, high-efficiency encoding technology is expected to play an important role in realizing distribution by a telecommunications system.

HDTV transmission at B-ISDN's STM-1 rate (155.52 Mb/s) or the existing PCM fourth group rate (97.728 Mb/s) is difficult because high quality is required of images reproduced and because high-speed processing is required as the sampling frequency is high.

An approach similar to prediction encoding used for standard TV is being tried for encoding HDTV signals. Table 1.4.3.2 shows examples of encoding. HDTV encoding using DCT is also under study.

In B-ISDN, HDTV is transmitted through an ATM network. In this case, the problem is the influence that cell discarding has on images. By dividing

Table 1.4.3.2. Prediction Encoding Systems for HDTV Signals

System	In-field prediction encoding (1)	In-field prediction encoding (2)	Inter-frame prediction encoding (1)	Inter-frame prediction encoding (2)
Signal form, band-width (MHz)	Y: 20 C_W: 7 C_N: 5.5	Y: 20 P_R: 7 P_B: 7	Y: 20 P_R: 7 P_B: 7	Y: 20 C_W: 7 C_N: 5.5
Sampling frequency (MHz)	Y: 48.6 C_W: 16.2 C_N: 16.2	Y: 44.55 P_R: 14.85 P_B: 14.85	Y: 44.55 P_R: 14.85 P_B: 14.85	Y: 48.6 C_W: 16.2 C_N: 16.2
Preprocess-ing	•Line offset subsampling •Chromatic signal line-sequential processing	•Line offset subsampling •Chromatic signal line-sequential processing	•Time-space filter •Time-division multiplexing •Chromatic signal line-sequential processing	•Time filter •Time-division multiplexing •Chromatic signal line-sequential processing
Encoding algorithm	•Previous value pre-diction DPCM •4-bit fixed-length encoding •Predicted value adap-tive quantum-ization •Noise correction filter	•Previous value pre-diction DPCM •Variable-length encoding •Adaptive quantumiza-tion	•Inter-frame extrapola-tion/in-field extrapola-tion, inter-polation adaptive prediction (pixel-unit) •Variable-length encoding •Adaptive scalar quan-tumization	•Inter-frame extrapola-tion/in-field extrapola-tion, inter-polation adaptive prediction (block-unit) •Variable-length encoding •Adaptive spectral/ scalar quan-tumization
Bit rate (Mb/s)	120/140	100/160	100/140	44/100/140

encoded information into most significant parts (MSP) that greatly affect picture quality and least significant parts (LSP) that do not, and sending MSP by the high-quality class and LSP by the low-quality class employing the ATM network's wire control, image reproduction is possible even when SLP cells are discarded, without leading to a grave picture quality deterioration (hierarchical encoding).

(iii) SLC System

When MUSE-AM is used, the bandwidth of HDTV original signals becomes 8.1 MHz (10 percent $\sqrt{R}$ (*cosine*) roll-off characteristics). For satellite broadcasting after FM modulation, the maximum frequency shift of images becomes 10.2 ±0.5 MHzp-p and the base bandwidth 27 MHz. The SLC system shown in Figure 1.4.3.3 is proposed as a method distributing MUSE-FM signals by a wired system. As the main parameters of this broadcasting satellite (BS) transmission system are basically the same as those of conventional satellite TV broadcasting, Bs signals can be transmitted by using the SLC system and communications satellite (CS) and other programs can also be transmitted by converting into the BS system.

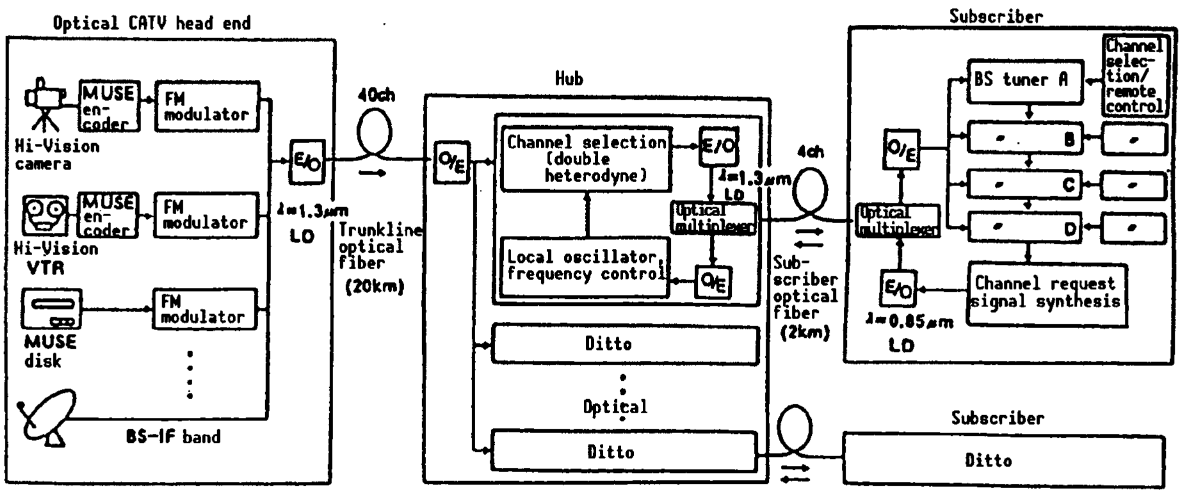

Figure 1.4.3.3. SLC System in HDTV

As the same scrambling system can be used, advanced scrambling comparable to that for BS programs is available.

1.4.4 Future Outlook

(1) Trend of Image Distribution Systems

(a) Multiple Channels, Multiple Outlets

So-called new media is expected to further increase the number of channels of image information services. Considering production efficiency (time and efficiency needed for production) of image information and high production cost, it seems difficult for the production division of image information to take off rapidly in the near future. As a result, an increase in channels means "distribution of the same or similar image information through various media or transmission channels." In other words, there will be "multiple outlets" phenomenon under which the same or similar image information is delivered to end users through different outlets.

This phenomenon represents a process toward the advent of society where really rich image information is distributed.

(b) Higher Picture Quality

Among image information services, there will be moves to improve the attractiveness of information itself through "differentiation" from other image services on the one hand and moves to provide the same or similar image information with higher picture quality for passive differentiation on the other.

HDTV has ultimate picture quality, but there are such moves between conventional TV image information and Hi-Vision image information, excepting wider screens and higher definition.

Irrespective of wireless or wire systems, real-time on line-image information services and package image information services always have competitive as well as coexisting relations. Their relationship is based on the fact that real-time and off-time characteristics complement each other.

Although these coexisting and mutually complementing relations have so far been maintained, competition for higher picture quality will become even keener if quality is given highest importance in future image information services.

This move can already be seen in the conventional TV system's moves toward improved-definition television (IDTV) and enhanced-definition television (EDTV) as well as moves in the United States to realize a wider aspect ratio with the simulcast method.

(c) Multiple Purposes

Media providing image information services are mutually broadband media. It is very natural to think it possible to offer image information services by adding a two-way transmission function to these image media while at the same time providing voice data with a far narrower band interactively.

From this, calls for multipurpose use of media arise.

This trend seems to have two different directions—moves by media supplying image information services to provide narrowband services and moves by media offering narrowband services to provide broadband services.

This broad trend is interesting. It is against this background that an integrated communications network concept is actively discussed today in connection with ISDN to provide conventional telephone, facsimile, and data communication services together with image information. With the telecommunications business liberalized now, it seems as if no regulation can limit the business.

However, it is certain that not everything should be subject to market principles.

(2) FTTH Concept

As discussions on the B-ISDN concept heats up, the FTTH concept is attracting attention. When FTTH is seen in this context alone, B-ISDN and FTTH look like two sides of a coin, actually, in many aspects they are not.

A specific service menu of B-ISDN includes various services from 64 kb/s POTS to bandwidth services for superbroadband high-speed data communications. When the bandwidth services are excluded on the grounds that they are for business purposes, there is no home-use services within a range of tens of Mb/s to more than 100 Mb/s, except relatively broadband image information services like facsimile, video phone, and teleconferencing services.

Meanwhile, TV broadcasting is deeply rooted in households like POTS telephones. If optical fibers are to be extended to homes, an optical fiber system that handles no TV broadcasting is unthinkable.

This is one of the reasons B-ISDN should link with FTTH. However, there is no clear inevitability of their link.

B-ISDN has cell-level quality deteriorations that affect ATM network quality—1) jittering in cell transfer delay, 2) errors in cell information, 3) cell loss and discarding, and 4) cell mixing-in. Transfer delay jitters and cell discarding are particularly important problems because they vary according to network traffic. When a massive amount of information is flowing in one direction, like image information, repeating cannot be done and the quality of reproduced images will be significantly affected. These technological problems indicate that B-ISDN is not suitable for image information distribution. Thus, B-ISDN is not necessarily being considered with image information distribution in mind.

This is one of the reasons why TV broadcasting services will not necessarily be included in the menu even if FTTH is adopted as the subscriber network of B-ISDN.

In view of these points and cost problems, it may still be a long time before FTTH will become a general subscriber network.

(3) Outlook

When seen from a broad point of view, there will not be signs for the time being of as rapid development of image information services as expected. The existing CATV services will continue to develop as before, using conventional technology. The foundation of CATV program suppliers will probably become solid after supply temporarily becomes unstable. As for FTTH using B-ISDN technology, only discussions on basic issues will continue with on-the-spot experiments carried out on an island-type futuristic experimental system.

The optical system could be introduced for CATV because DFB-LD will become easy to use in terms of both performance and cost. Japan's CATV systems have been trying from the beginning to achieve higher picture quality than that of their U.S. counterparts and it is thus hard to say that they will immediately go for the SCM system.

This CATV trend will lead to improving CATV services. Improvement in picture quality of CATV systems will expedite improvement in source picture quality on the part of program suppliers.

Under the current situation, the most vital thing is to improve image information services further in terms of content and picture quality. Top priority should be given to solving these immediate problems and much time will be spent to improve the basics.

The starting point of future developments will be when technical aspects of B-ISDN on image transmission are solidly in place.

It will also be important for people concerned to cooperate in making image information services a national priority. To that end, it will be necessary to provide opportunities nationwide for the general public to directly recognize the benefits of image information. (Yamamoto)

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1.5 Terabit Optical Transmission

A 2.5 Gb/s (STM-16) optical transmission system based on the Synchronous Digital Hierarchy (SDH) international standard has entered a commercial phase and the development of 10 Gb/s optical transmission technology as the next system is getting into high gear. This corresponds to 155,000 of 64 kb/s voice circuits. When a network mainly for images using STM-1 (155 Mb/s) as one-circuit image channel is assumed, 10 Gb/s corresponds to only 64 circuits. The development of terabit optical transmission technology thus becomes an important issue toward the 21st century.

This section deals with the current development trend toward the realization of terabit optical transmission technology. As the trend until FY89 is reported in detail in the OPTICAL TECHNOLOGY TREND RESEARCH REPORT (March 1990), this report will introduce the development trend after that, quoting announcements at international meetings.

1.5.1 Current Status and Trend of Trunk Line Optical Transmission Technology

Here, the recent development trend of trunk line optical transmission technology is introduced by classifying direct detection systems as superhigh-speed optical transmission technology and heterodyne or homodyne detection systems as coherent optical transmission technology.

(1) Superhigh-Speed Optical Transmission Speed

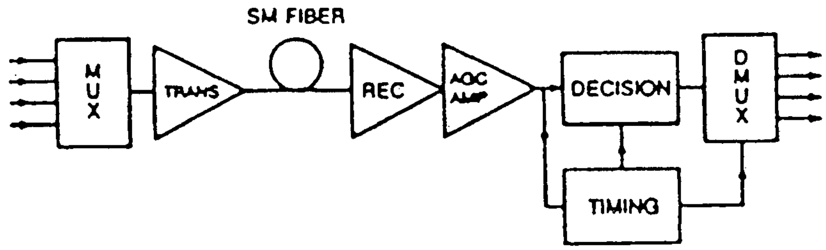

Figure 1.5.1.1. Structure of Superhigh–Speed Optical Transmission System (by J.L. Gimlett[1])

Most optical transmission systems so far put to practical use are direct detection systems. Figure 1.5.1.1 shows a typical system configuration. Active efforts are under way to develop a superhigh–speed optical transmission system with a speed of more than 10 Gb/s using this system.[1] Each section of the configuration has problems that must be solved and various methods and devices are compared and studied. Optical transmission systems, optical reception systems, electronic device technology, and recent transmission experiments are introduced below.

(a) Optical Transmission Systems

As transmission speeds enter the superhigh range, waveform distribution stemming from dispersion characteristics of optical fibers poses a problem in long–distance transmission. Therefore, a reduction of chirping at the time of superhigh–speed modulation is a big issue for optical transmitters. For the intensity modulation (IM) system, direct modulation of the light source and the use of an external modulator are being studied.

The problem involved in direct modulation is how to improve the performance of semiconductor lasers used as light sources. The introduction of λ/quaternary phase–shift keying structure for the DFB laser and the multiple quantum well structure for the active layer is being considered and their introduction is confirmed to have modulation and low–chirping effects at more than 10 Gb/s. Figure 1.5.1.2 shows the configuration of a system for a transmission experiment using a 15 μm–band DFT laser and dispersion–shift optical fiber and its encoding error rate characteristics.[2] By double–multiplexing 5.5 Gb/s signals to make 11 Gb/s signals and after direct modulation of the DFB laser, the signals are transmitted over 81 km and 93.8 km dispersion–shift optical fibers. A bandwidth of 16 GHz is achieved by combining PIN photodiodes and a high electron mobility transistor (HEMT) amplifier as an optical receiver. Little distribution is observed after 81 km transmission. Further, a 93.8 km transmission experiment was conducted using a semiconductor optical amplifier to show the possibility of long–distance transmission by an optical amplifier.

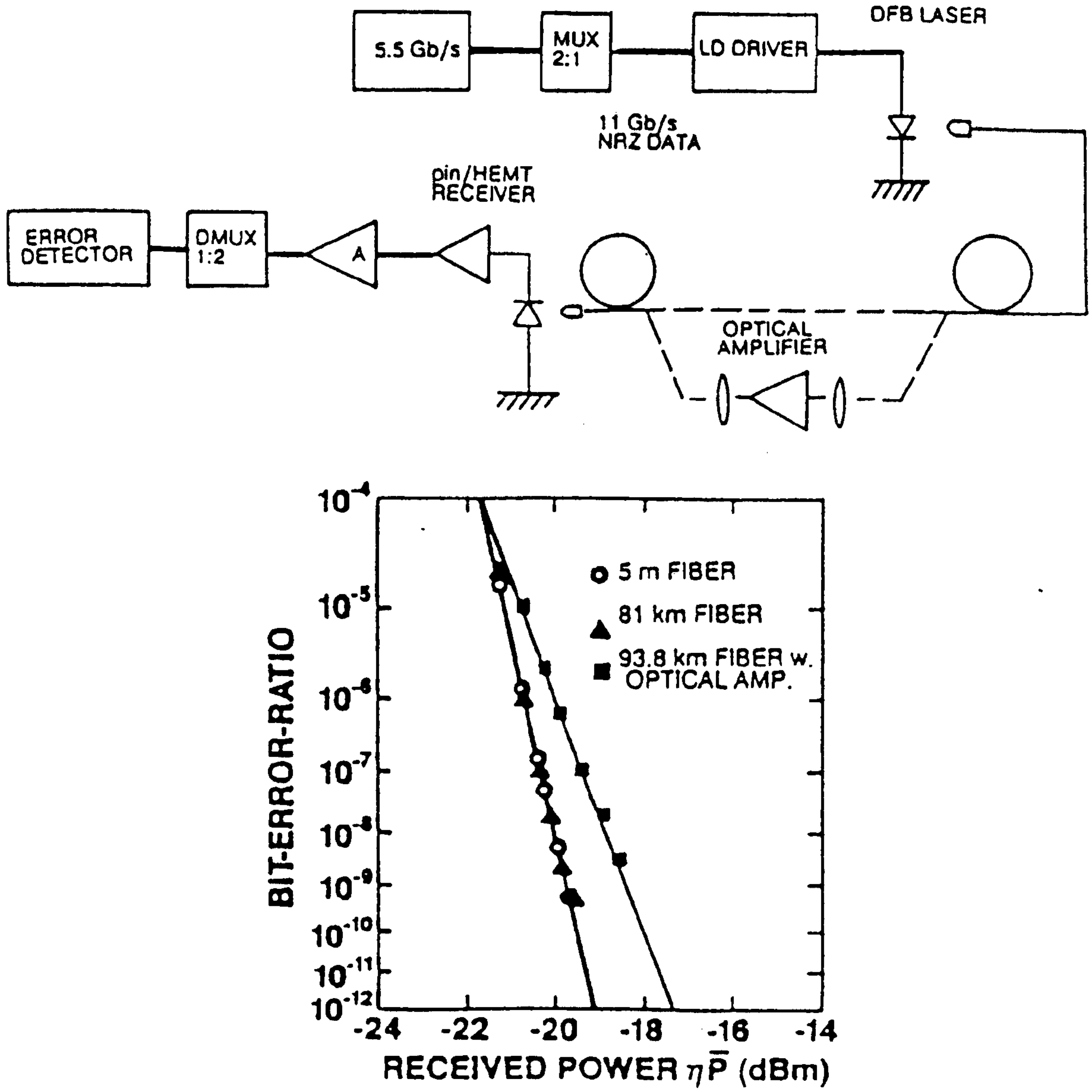

Figure 1.5.1.2. Structure of Direct Modulation 11 Gb/s Transmission Experiment System and Encoding Error Rate Characteristics

However, directly modulating a semiconductor laser in order to realize a 1.55 μm-band superhigh-speed optical transmission system using standard optical fiber with zero dispersion around the 1.3 μm band involves the very difficult problem of lowering chirping. Therefore, active efforts to develop an external modulation method are also under way.[3,4,5] External modulators widely studied are the Mach-Zehnder modulator made of $LiNbO_2$ and the electric field absorption-type modulator made of InP. Figure 1.5.1.3 shows these external modulation systems and the transmission limits of the DFB laser direct modulation system arising from the optical fiber dispersion characteristics, defined by the dispersion value that generates a distribution of 0.5 dB.

From the figure, it is apparent that the external modulation systems sharply improve the transmission limit dispersion value and the use of the Mach-Zehnder modulator improves it to more than 500 ps/nm, enabling transmission over tens of km even with ordinary optical fibers. Although there are still such problems as a reduction in the modulation voltage and drift compensation, the use of an external modulator is a promising method in that it can be integrated with a DFB laser, though it cannot improve the transmission limit dispersion value as much as the $LiNbO_2$ Mach-Zehnder modulator. Figure 1.5.1.4 shows an example of such an integration and the emitted light spectrum broadening in a 10 Gb/s modulator is confirmed to be 0.1 Å or less. A unique method to avoid influence of optical fiber dispersion characteristics has also been proposed. Under the method, the light source is modulated by the differential phase-shift keying (DPSK) method and DPSK signals are amplitude-modulated by an interferometer on the receiving end for direct detection.[6,7] Figure 1.5.1.5 shows an experimental system configuration and the results of a transmission experiment. The light source is a 1.55 μm-band DFB laser and DPSK signals are directly obtained by impressing 10 Gb/s modulated signals to the injected current. The signals are converted into bipolar signals at NRZ in order to avert the DFB laser's uneven FM modulation frequency characteristics. After transmission over an optical fiber cable, Mach-Zehnder optical fiber interferometer on the receiving end converts the DPSK signals into ASK signals for direct detection. As is clear from the

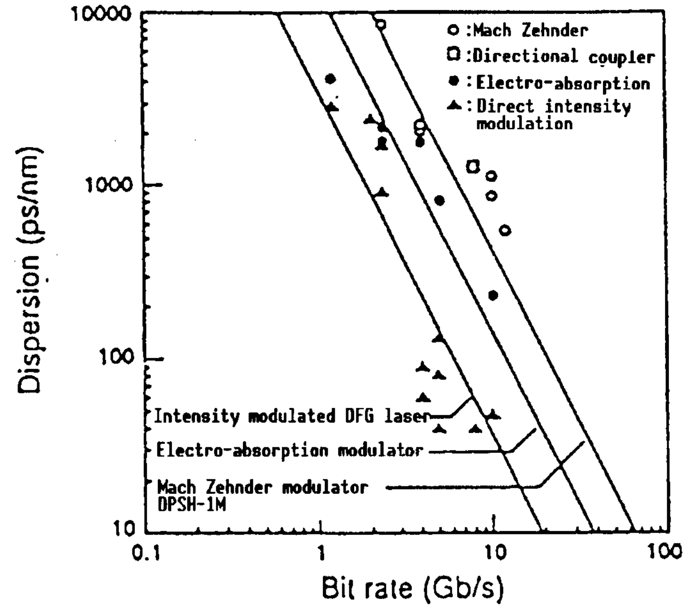

Figure 1.5.1.3. Comparison of Transmission Limit Dispersion Value in Intensity Modulation[3]
The transmission limit dispersion value is defined at 0.5 dB deterioration.
(By H. Hinishimoto)

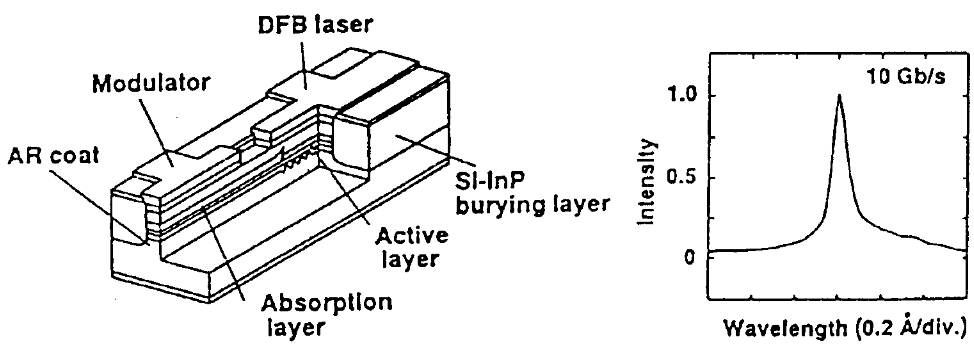

Figure 1.5.1.4. Structure of Light Source Integrating Electric Field Absorption Modulator and DFB Laser, and Emission Spectrum Characteristics at Time of 10 Gb/s Modulation
(By H. Soda, et al.[5])

encoding error rate characteristics shown in the figure, little deterioration is observed up to 48.5 km and the results are similar to those of a system using the $LiNbO_3$ Mach-Zehnder external modulator.[3] This DPSK modulation/direct detection method is worthy of consideration for superhigh-speed optical transmission using standard optical fibers with 1.3 μm-band zero dispersion in that it requires no external modulator.

(b) Optical Receiving System

A broad band and high sensitivity are required of a superhigh-speed optical receiver. An optical receiver with a bandwidth of 16 GHz using a PIN photodiode has been developed for a broader bandwidth, but its receiving sensitivity is not high enough. In conventional optical transmission systems, the avalanche photodiode (APD) has been widely used as a device satisfying both, but for use in a superhigh-speed optical transmission system 10 Gb/s or faster, it is problematic in terms of the gain-bandwidth product. Recently, attempts have been made to expand the gain-bandwidth product by employing the superlattice structure for the APD's avalanche doubling layer. The reception sensitivity of −24 dBm has been achieved against 10 Gb/s RZ signals in these attempts[9] and the advance of this approach is called for.

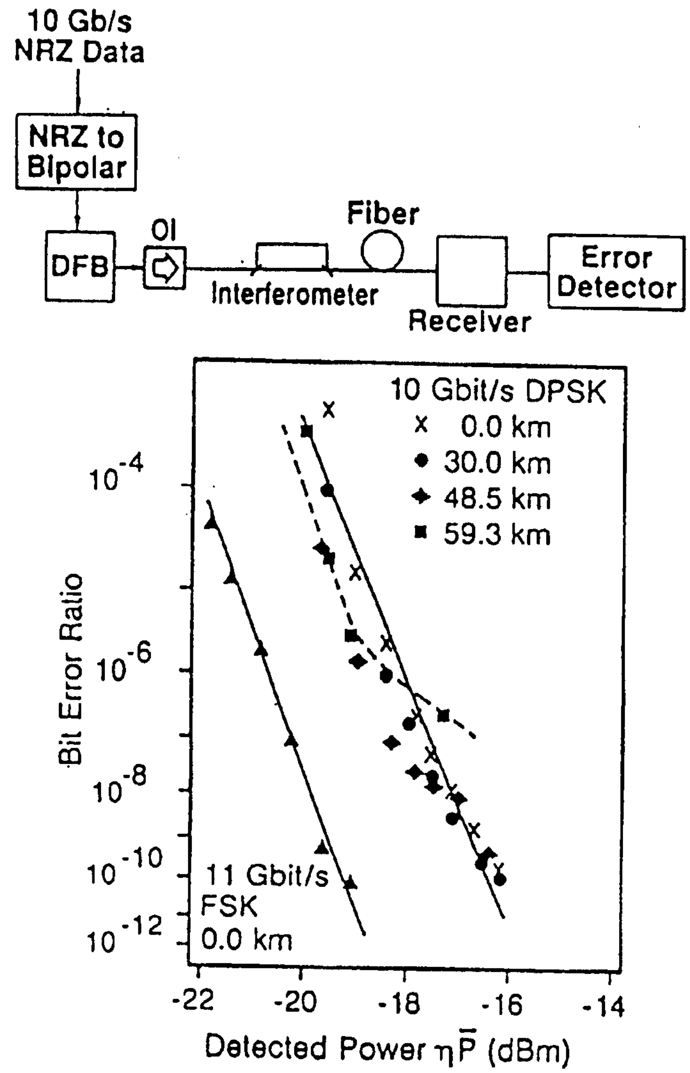

Figure 1.5.1.5. Configuration of 10 Gb/s DPSK Modulation/Direct Modulation Experiment System and Encoding Error Rate Characteristics (By R.S. Vodhanel, et al.[7])

The remarkable advance of optical amplifiers in the past few years is a big step toward the solution of problems involved in high-sensitivity optical reception technology. The optical fiber amplifier using an erbium-doped optical fiber, in particular, does not depend on polarization and the loss in coupling with optical fibers for the transmission path is small. Therefore, it is expected to be used not only as a preamplifier to boost optical receiver sensitivity but also as a post-amplifier to increase optical transmission output and a 1R booster for transmission over a longer distance. When used as

a preamplifier, it improves sensitivity to −30.8 dBm at 10 Gb/s.[10] But an optical fiber transmission experiment showed that return light due Rayleigh scattering from the transmission path optical fiber and its multiple reflection affect the optical fiber amplifier's noise characteristics, and it is pointed out that device designing requires special care, such as the insertion of an isolator to the input side.[10,11] The optical fiber amplifier will no doubt become an important device in developing future optical reception systems. In parallel with the development of optical fiber amplifiers, research and development of semiconductor optical amplifiers are also under way. Semiconductor optical amplifiers are characterized by a broad amplified waveform bandwidth, unlike optical fiber amplifiers. But it also has hurdles to clear before being put to practical use—dependence on polarization stemming from the waveguide structure and a large loss in coupling with optical fibers. Figure 1.5.1.6 shows the current status of reception sensitivity of various optical receiving systems. Those systems are still under development and a further increase in sensitivity is called for.

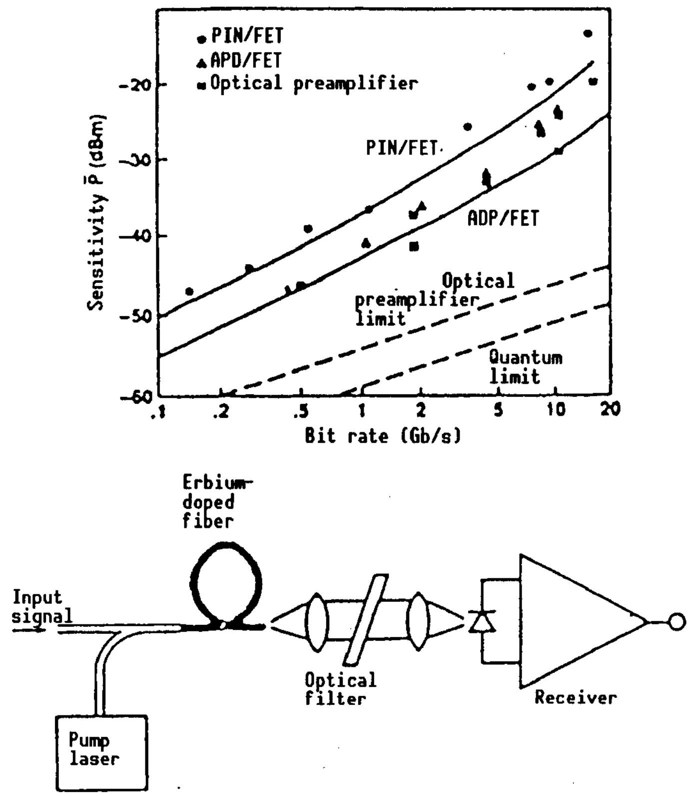

Figure 1.5.1.6. Sensitivity Comparison of Various Optical Reception Systems (J.L. Gimlett, et al.[1])

(c) Optical Fiber Dispersion Compensation Technology

It has been noted that optical fiber dispersion characteristics are a major factor limiting the transmission distance in superhigh-speed optical transmission. To solve this problem, equalization and compensation of dispersion characteristics are being studied.

For equalization on the receiving end, it has been proposed to insert a reflective single-cavity interferometer or Fabry-Perot etalon before the optical receiver for phase equalization.[12] Using standard optical fibers, this idea has proved to allow 61.5 km transmission at 5 Gb/s.

A dispersion compensation method involving prechirping on the transmitting end has also been proposed.[13] Figure 1.5.1.7 shows its configuration. A DFB laser is FM-modulated by bit-synchronized sine waves and the optical output is intensity-modulated by an external electric field absorption modulator. Placing low-frequency components before and high-frequency components after

the transmission pulse causes pulse compression first upon its propagation over a negative-dispersion optical fiber and then pulse width expansion occurs as propagation progresses, but the transmission distance can be increased. In a 50 km transmission experience at 10 Gb/s using a standard optical fiber, prechirping could reduce deterioration to 0.8 dB.

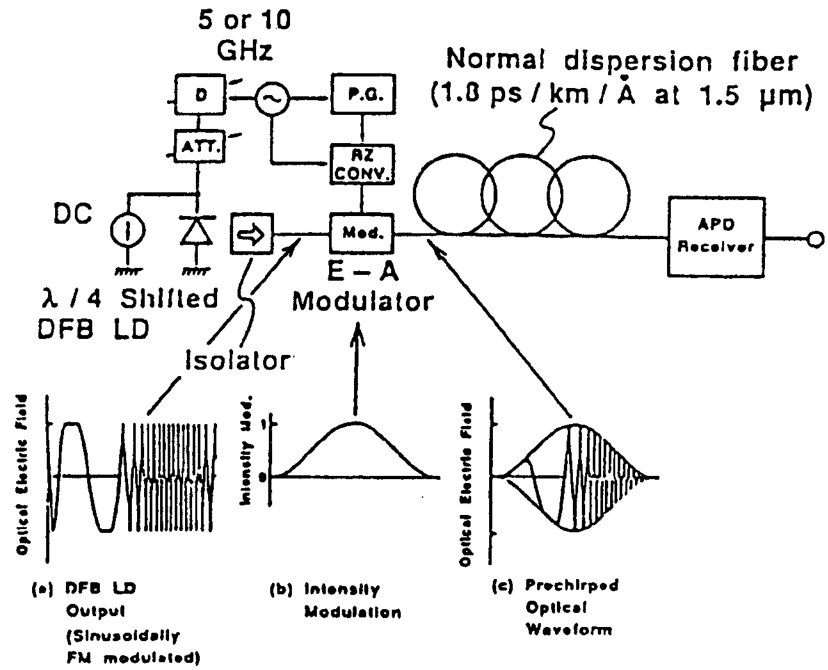

Figure 1.5.1.7. Structure of Prechirp Technique Dispersion Compensation Transmission System (T. Saito, et al.[13])

These dispersion compensation technologies are technically unique and interesting. But it is difficult at present to judge if they are technologies that hold the key to realizing superhigh-speed optical transmission as that also depends on progress in optical transmission technology. These should be studied while keeping tab on the progress of optical transmission technology.

(d) Electronic Device Technology

Electronic device technology is also important technology supporting superhigh-speed optical transmission. The progress of Si IC technology has opened the way for using Si ICs for the optical transmission/reception circuit and multiplexing/demultiplexing circuit for Gb/s transmission. But for the superhigh-speed sector of over 10 Gb/s, test product assessment started only recently for small-scale ICs that use GaAs FETs, GaAs HBT, and Si bipolar transistors as basic devices.

Table 1.5.1.1 shows major results obtained so far.[1] An IC using GaAs DMT (hetero-MISFET) as the basic device has been developed. It achieved a rise/fall time of 40 ps and operation at 10 Gb/s when incorporated into a laser module.[14] A two-stage amplifying IC using GaAs HBT has been test-manufactured as a preamplifier and it achieved a bandwidth of 10 GHz, transimpedance of 57 dB ohm and input conversion noise current of 12 pA/$\sqrt{Hz}$.[7] As for the multiplexing/demultiplexing circuit, 0.6 μm-emitter Si bipolar transistor,[16] an 0.15 μm GaAs FET IC[17] operating at 11 Gb/s, and a GaAs HBT IC operating at 15 Gb/s have been reported. In each case, only the basic circuit is made of an IC and the device process is not industrially perfected yet. Which becomes the mainstay device must await future comparative assessment.

Table 1.5.1.1. Current Status of Superhigh-Speed Electronic Devices (By J.L. Gimlett[1])

IC	Technology	Speed (Gb/s)	Organization
2:1 MUX	Si bipolar	11	Bellcore/Avantek Siemens/Rub
	GaAs MESFET	11	NTT
	GaAs HBT	15	Toshiba
Laser driver	GaAs DMT	10	NEC
Preamplifier	GaAs HBT	10	Toshiba
Decision circuit	Si bipolar GaAs HBT	11 10	Bellcore/Avantek Toshiba
Sonet framer	GaAs FET	2.5	Bellcore

There has also been progress in InGaAs HEMT and HBT. As these electronic devices match well with InP/InGaAs, materials for long wavelength-band optical devices, the integration of an optical device with an electronic device, i.e., an optoelectronic device (OEIC), is expected. Figure 1.5.1.8 shows a cross-sectional view of an OEIC integrating a λ/quaternary phase shift DFB laser and 2:1 multiplexing circuit. The electronic device uses InGaAs MODFET as the basic device and operates at 10 Gb/s.[18] Further discussions on the necessity of OEIC are needed, but its possibility should be studied as future technology.

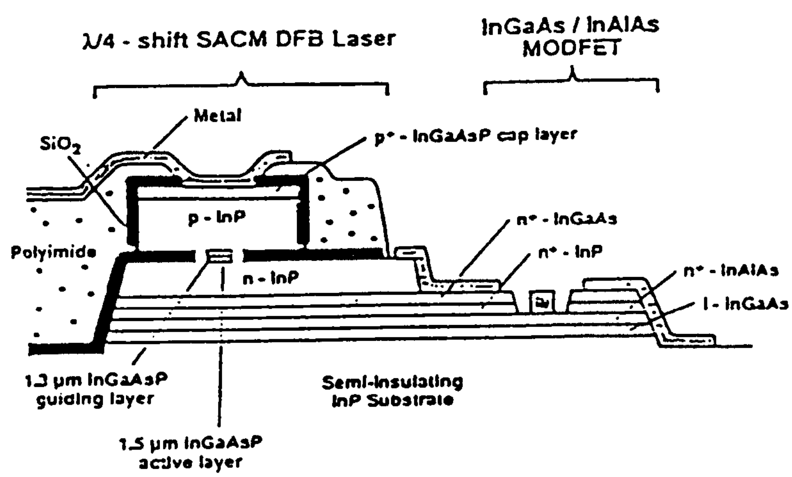

Figure 1.5.1.8. Device Structure of 10 Gs/b OEIC Transmitter (By T.P. Lee, et al.[18])

(e) Superhigh-Speed, Long-Distance Transmission Experiment

As explained above, devices still have problems to be solved for 10 Gb/s optical transmission. But with improvements in methods, there are now signs of the realization of such transmission. Transmission experiments worthy of note from the viewpoint of long-distance transmission have been reported and an example of such experiments is shown below.

Figure 1.5.1.9 is the structure of a 17 Gb/s, 150 km transmission experimental system.[19] It uses a 1.55 μm-band DFB laser as the light source, which is intensity-modulated by an $LiNbO_3$ Mach-Zehnder external modulator and amplified by an optical fiber amplifier to attain an optical output of +9.8 dbm. The optical fiber used is a dispersion-shift type with a loss of 0.21 dB/km and the optical receiver uses the optical fiber amplifier as a preamplifier to achieve reception sensitivity of −24 dBm. In order to compensate optical fiber residual dispersion characteristics, a standard optical fiber having zero dispersion in the 1.3 μm band is used for equalization and the operation point of the Mach-Zehnder external modulator is optimized for transmission over a distance of 150 km with little deterioration.

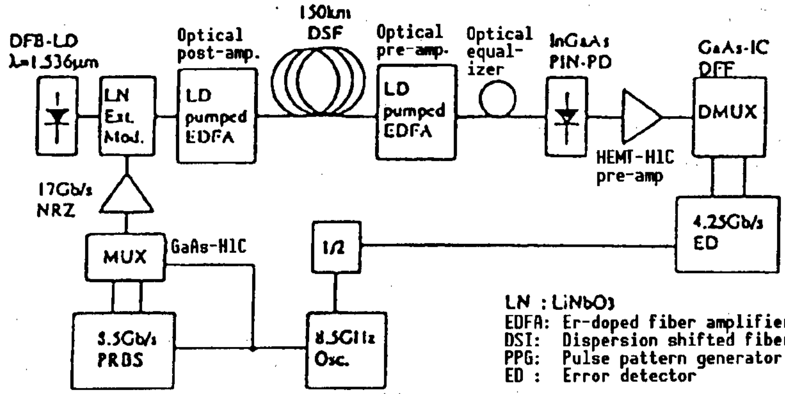

Figure 1.5.1.9. Configuration of Experimental 17 Gs/b, 150 km Optical Transmission System (By K. Hagimoto, et al.[19])

Figure 1.5.1.10 shows the structure of a 10 Gb/s long-distance transmission experiment system which uses an optical fiber amplifier as a 1R booster.[20] Transmission over a distance of 375 km at 10 Gb/s is possible by insetting an optical fiber amplifier about every 100 km.

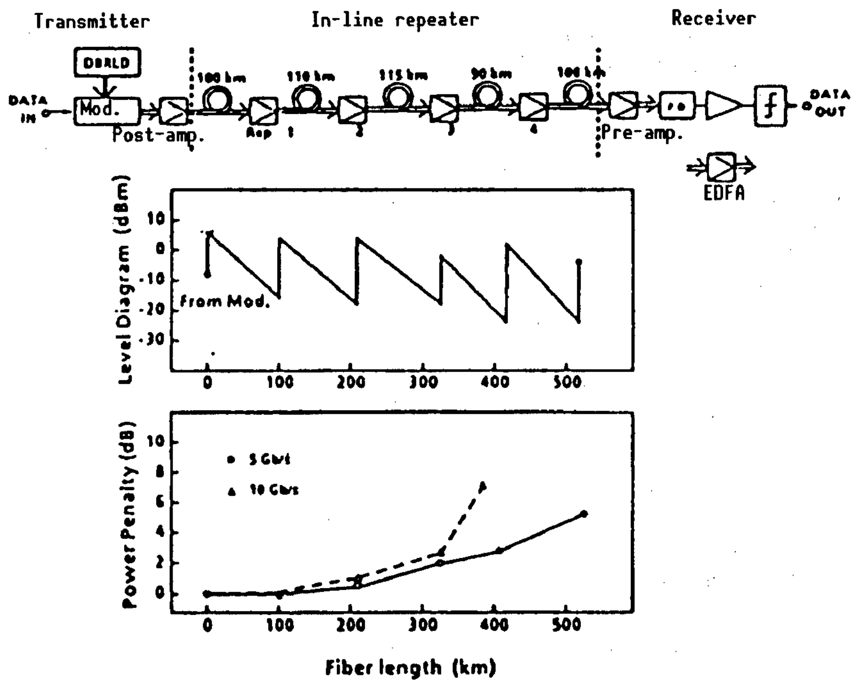

Figure 1.5.1.10. Configuration of Experimental 10 Gb/s, 375 km Optical Transmission System and Evaluation Results (K. Nakagawa, et al.[20])

Optical Multiplex Transmission Technology

926C1015E Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 92-102

[Text] **1.5.2 Current Status and Trend of Optical Multiplex Transmission Technology**

Together with a boost in the speed of the basic optical transmission systems introduced in 1.5.1, the development of optical domain multiplexing technology is also important for the realization of terabit optical transmission. Optical domain multiplexing can be broadly classified as optical frequency multiplexing and time multiplexing. Of the former category, the direct detection super-high-speed optical transmission system that uses no optical frequency is generally called wavelength-division multiplexing (WDM) and the coherent optical transmission system is called optical frequency-division multiplexing (OFDM), whose development trends will be introduced below.

(1) WDM Transmission Technology

WDM transmission is an optical multiplexing system that has been under experimentation since the early stages of optical transmission technology and is already used as an option in increasing transmission capacity. WDM has been the multiplexing of two wavelengths, such as WDM transmission of wavelengths of 1.3 μm and 1.55 μm. But the advent of the DFB laser and a sharp improvement in the performance of semiconductor lasers for coherent optical transmission made it possible to have semiconductor lasers with different wavelengths in the same wavelength range, for example, in the 1.55 μm band. This activated studies on multiple-wavelength WDM transmission systems aimed at a larger transmission capacity.

Figure 1.5.2.1 shows the configuration of an experimental 2.4 Gb/s four-channel WDM transmission system designed as an option for increasing the capacity of a submarine cable system and the results of an experiment.[1] The transmission light sources used are DFB lasers with the wavelengths at 2-nanometer intervals of 1,548.8 nm, 1,550.8 nm, 1,552.7 nm, and 1,554.7 nm and 2.4 Gb/s modulation is done by an $LiNbO_3$ Mach-Zehnder external modulator. These are mixed by a 4 x 4 optical fiber star coupler and amplified by an erbium-doped optical fiber amplifier to obtain an output of +3 dBm.

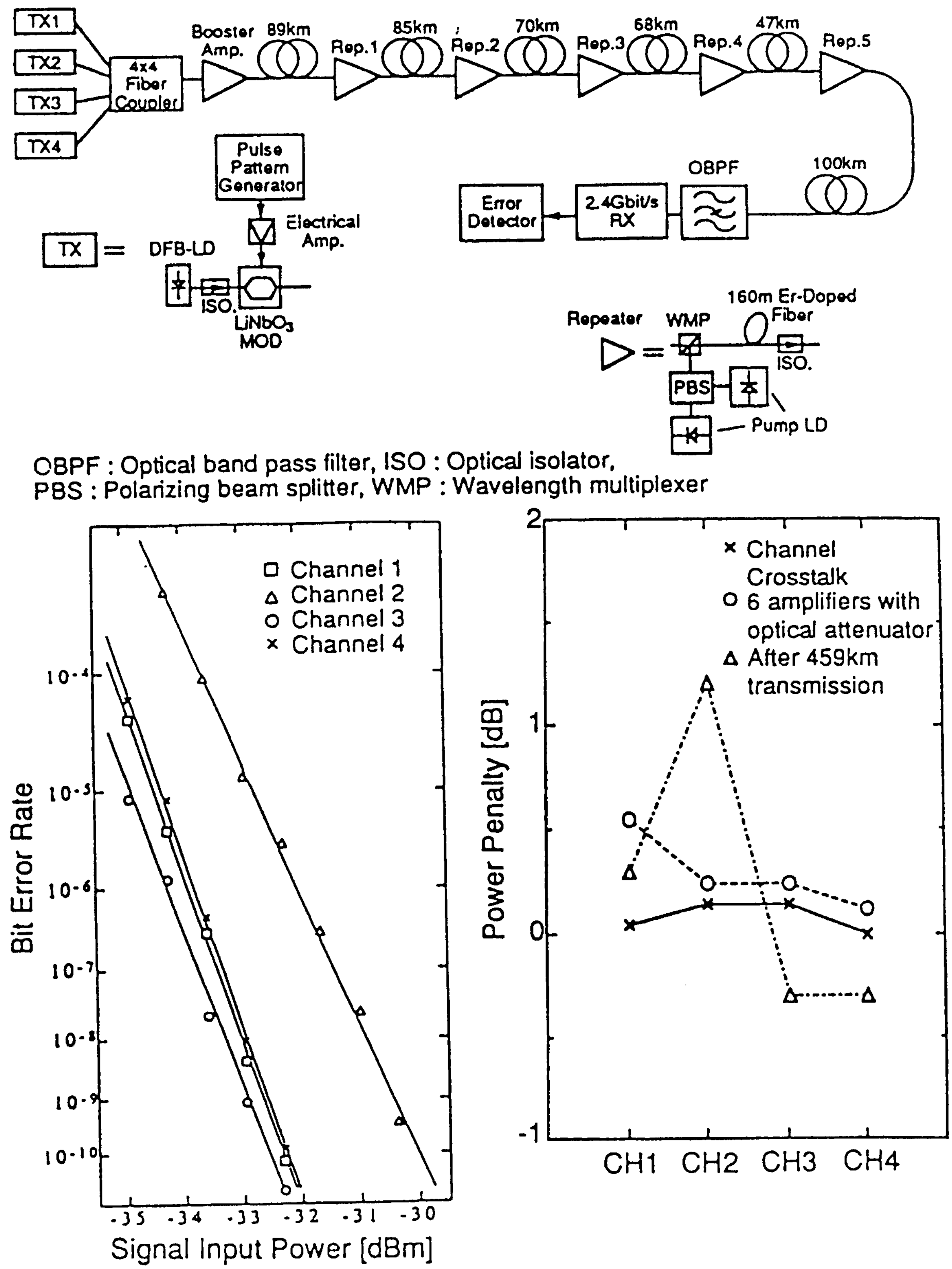

Figure 1.5.2.1. Configuration of 2.4 Gb/s, 4-Channel WDM Transmission Experiment System and Experiment Results (H. Taga, et al.[1])

The transmission line optical fibers are standard single-mode optical fibers and five optical fiber amplifiers are used to make a 459-km long transmission line. In the transmission experiment, an optical filter with a bandwidth of 1 nm was inserted to assess encoding error rate characteristics of a desired channel. As the experiment results in the figure show, no floor phenomenon appears in any channel until the encoding error rate of 10^{-10} or lower and deterioration caused by crosstalk between channels is extremely small, proving that the method is a promising one for increasing the capacity of long-distance transmission systems. The same group of researchers has also reported on a 4 Gb/s, two-channel, 330 km WDM transmission experiment using a similar system configuration.[2] Figure 1.5.2.2 is the configuration of an experimental 10 Gb/s four-channel WDM transmission system aimed at a larger capacity. It uses 1,531.3 nm, 1,539.9 nm, 1,547.2 nm, and 1,553.2 nm four-wavelength λ/quaternary phase-shift DFB lasers as the transmission light sources and each laser is directly modulated by 10 Gb/s NRZ signals.[3] In a transmission experiment using 40 km dispersion-shift single-mode optical fibers as the transmission line and a semiconductor optical amplifier as a preamplifier, there was no deterioration caused by crosstalk.

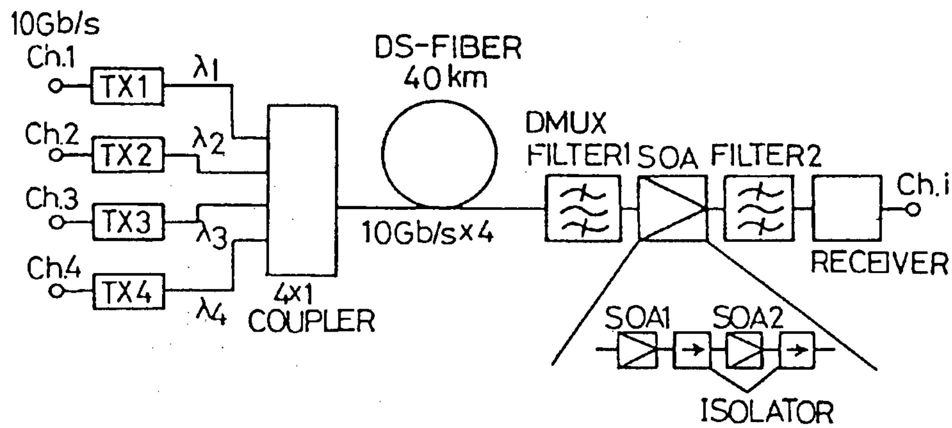

Figure 1.5.2.2. Configuration of Experimental 10 Gb/s, 4-Channel WDM Transmission System (By H. Nakano, et al.[3])

As an example of high wavelength-multiplexing WDM transmission experiments, an experimental 16-channel WDM transmission system designed as a broadband subscriber distribution system has been reported as shown in Figure 1.5.2.3.[4] The transmitter uses 16 DFB lasers with wavelengths of 2 nm intervals from 1,527 nm to 1,557 nm and direct modulation is done. Transmission output is distributed by a star coupler for transmission over 10 km single-mode optical fibers. Optical output is divided by a 1 x 4 coupler on the transmitting end and a tunable etalon with a bandwidth of 0.25 nm is installed on each receiving end for the selection of a desired channel. The system proved to have little crosstalk in 600 Mb/s and 2 Gb/s transmission experiments. A 100-channel experiment has also been reported as an example of WDM transmission experiments with even higher wavelength multiplexing.[5] Figure 1.5.2.4 shows the configuration of that experimental system and experimental results. The transmitter uses 100 DFB lasers with wavelength intervals of 10 GHz in the 1.55 nm band, i.e., about 0.08 nm intervals in terms of optical wavelength. The DFB lasers' spectral linewidth is 20 MHz or lower. Modulation is 600 Mb/s FSK modulation and conversion from FSK to ASK is done by an optical frequency discriminator on the receiving end for direct detection.

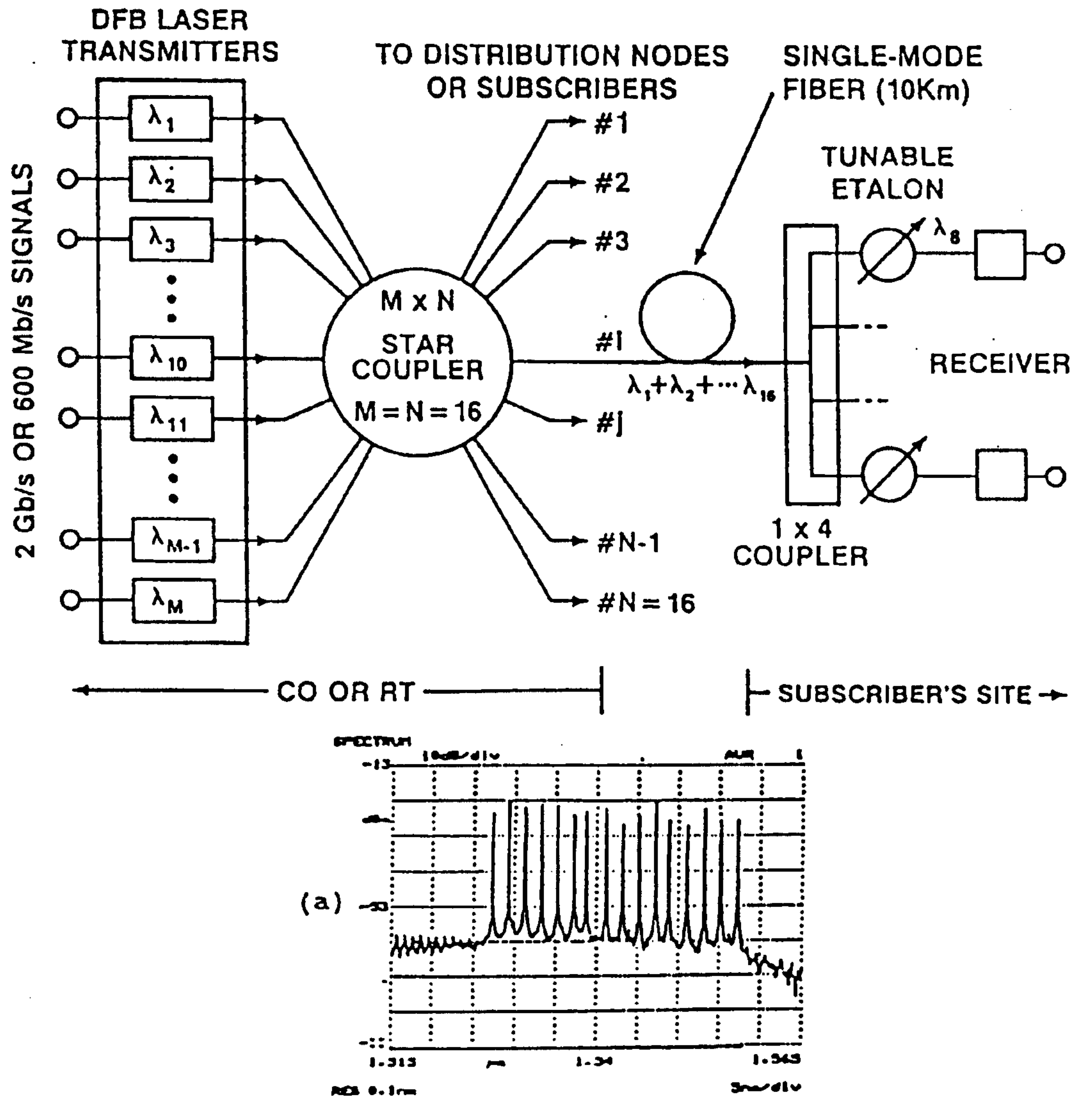

Figure 1.5.2.3. Configuration of Experimental 16-Channel WDM Distribution Transmission System (C. Lin, et al.[4])

A multiple-stage connection Mach-Zehnder filter is used for optical channel selection, with tuning done by heating the filter. Crosstalk is 13 dB or lower for any channel. As the encoding error rate characteristics in the figure show, there is no reception sensitivity deterioration after transmission over either a 50.5 km standard single-mode optical fiber or a 26 km dispersion-shift optical fiber. There is little influence of four-wave mixing caused by increased optical voltage density within the optical fiber stemming from multiple channels.

The above example shows the possibility of WDM multiplexing of up to 100 channels, marking a big step toward the realization of terabit optical transmission. WDM transmission of 100 channels is applicable to coherent

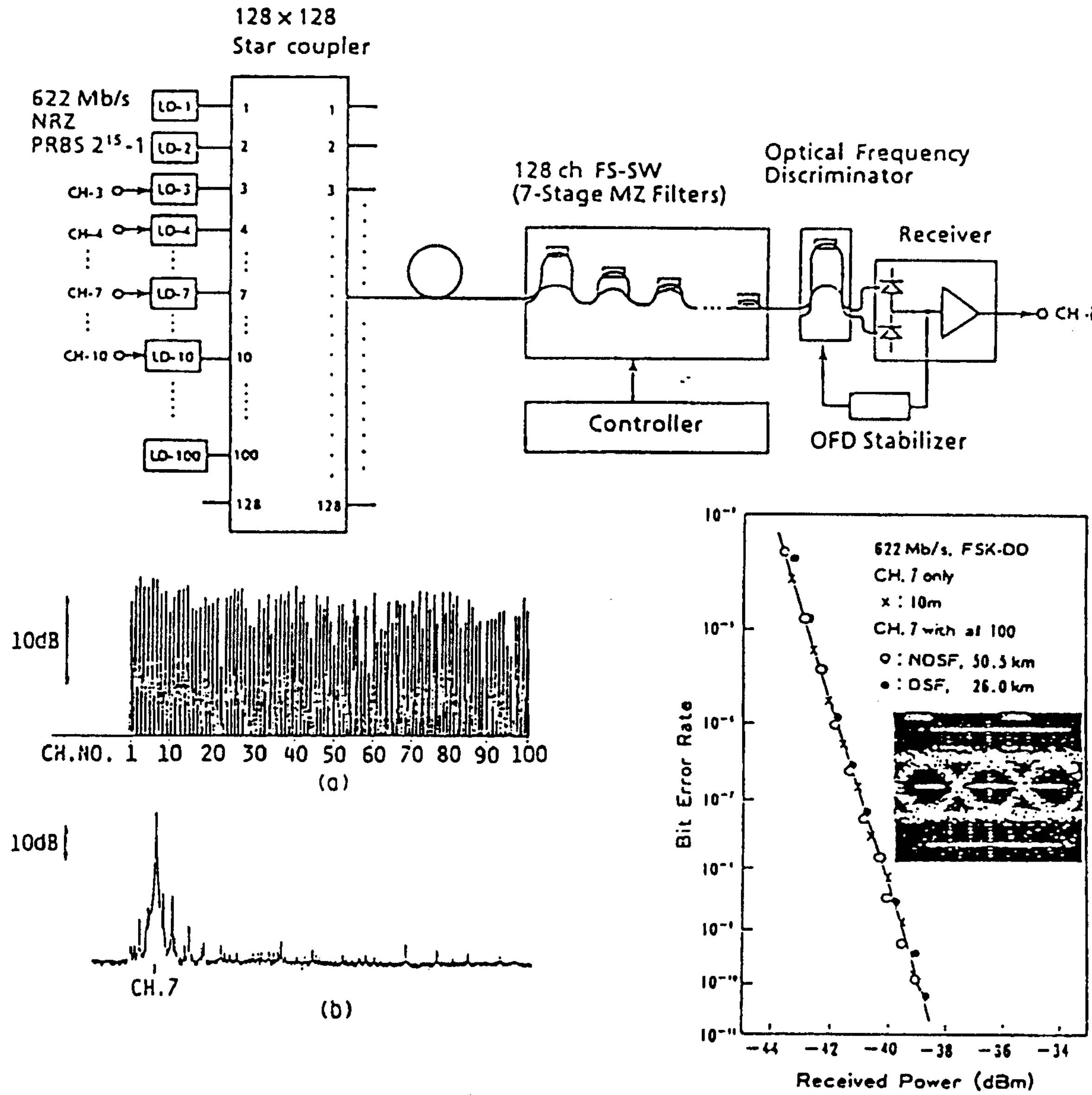

Figure 1.5.2.4. Configuration of Experimental 100-Channel WDM Transmission System and Experiment Results (By H. Toba, et al.[5])

optical transmission by changing the detection to heterodyne detection and thus can be seen as OFDM transmission.

(2) OFDM Transmission Technology

Like WDM transmission technology, OFDM transmission technology is being developed from the two viewpoints of distribution of multiple-channel signals and large-capacity transmission by increasing the number of channels.

Figure 1.5.2.5 compares OFDM transmission technology and WDM transmission technology from the viewpoint of distribution transmission. OFDM is more advantageous than WDM for multiplexing of up to around 100 channels and its combination with optical amplifiers can distribute signals to more than 10,000 subscribers.[6] Experiments on OFDM distribution transmission systems are under way.[7,8,9] Figure 1.5.2.6, an example of such experiments, is the configuration of an experimental 140 Mb/s FSK modulation/heterodyne detection multiple-channel TV distribution transmission system.[7] The experimental system is equipped with four optical transmitters and signals are distributed by a 16 x 16 star coupler, transmitted over an 11 km standard single-mode optical fiber and then distributed to each receiver by a 1 x 16 star coupler. A transmission experiment showed that there is still a power margin to make possible 16 distributions, i.e., distribution to 1,024 (=16 x 16 x 16) subscribers. OFDM distribution transmission systems with an even larger number of channels are expected to be developed in the future.

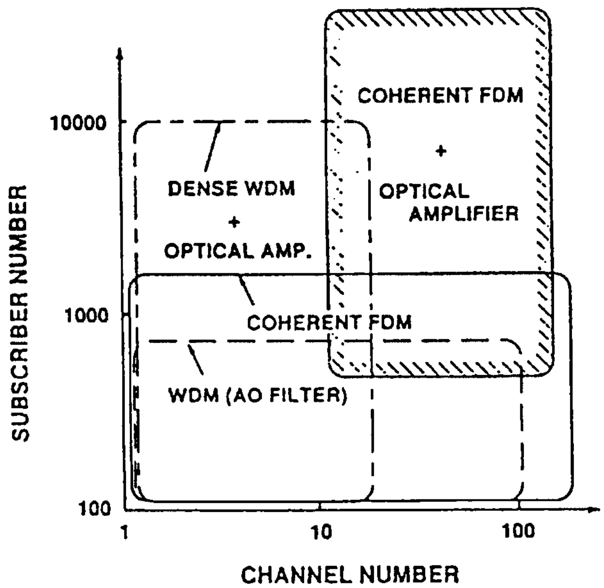

Figure 1.5.2.5. Relations Between Number of Channels and Number of Channels and Number of Distribution in WDM and OFDM Transmission (By S. Yamazaki and K. Emura[6])

There is also progress in the development of OFDM transmission technology toward the realization of large-capacity transmission of more than 100 Gb/s. Under this system, it is necessary to narrow optical frequency intervals of channels for high-density multiplexing, and crosstalk between channels becomes a problem in this context.[10] Figure 1.5.2.7 shows the configuration of an experimental 2.5 Gb/s multiple-channel OFDM transmission technology and the possibility of a boost in transmission capacity based on the result of its analysis.[11,12] The four-channel optical transmitter uses 1.54 μm-band multiplex quantum well DFB lasers, FSK

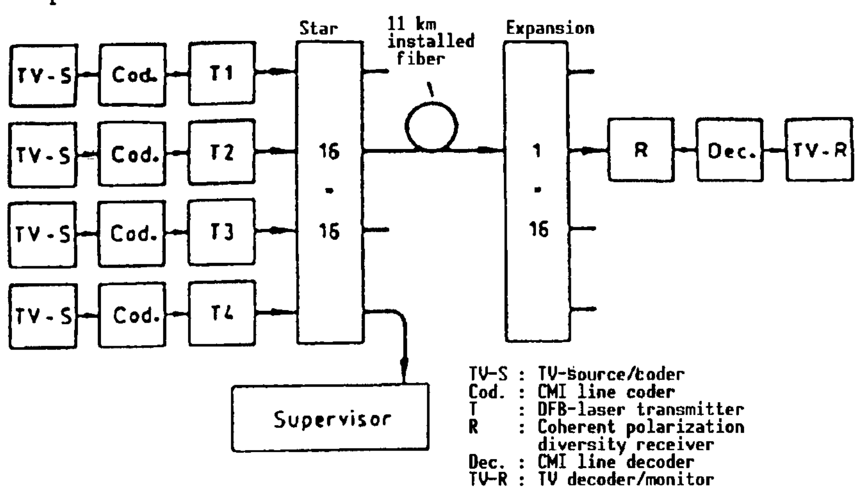

Figure 1.5.2.6. Configuration of Experimental OFDM Distribution Transmission System (By T. Beck, et al.[7])

modulated at 2.5 Gb/s. The receiver has functions to control polarization of each channel simultaneously, control broadband channel intervals, and distinguish channels. The four channels' transmission output ranges from +5.9~7.8 dBm and reception sensitivity from -43.5~-43.0 dBm, with an allowable span loss of about 50 dB. Crosstalk for multiple-channel OFDM transmission is determined by channel intervals and intermediate frequency bandwidth. Their optimization is required to increase channel interval density and lower crosstalk. A four-channel OFDM transmission experiment using a multiplexer/demultiplexer with channel intervals set at 15 GHz showed that there is little reception sensitivity deterioration arising from crosstalk. The allowable span loss in this case is about 39 dB, allowing 150 km transmission by an optical fiber with loss of 0.24 dB/km. These results indicate that, as shown in the figure, the allowable span loss is about 13 dB even when the capacity is increased to 64 channels, i.e., 160 Gb/s (=2.5 Gb/s x 64), enabling 60 km transmission.

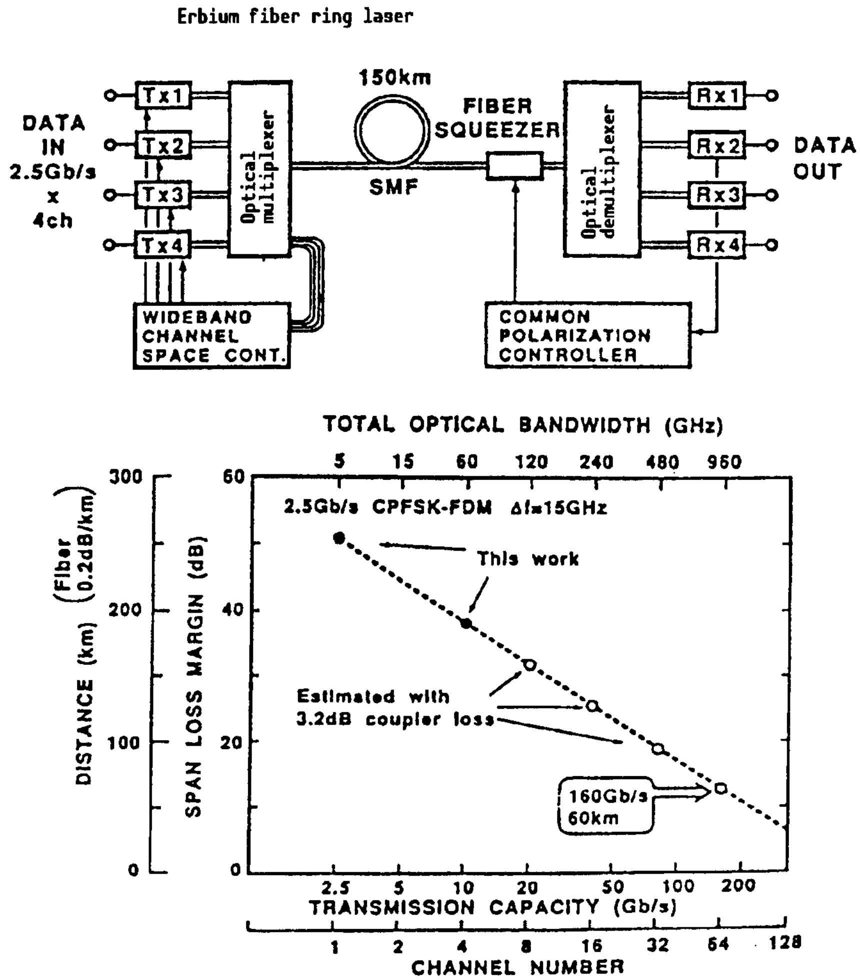

Figure 1.5.2.7. Configuration of Experimental 2.5 Gb/s, 4-Channel OFDM Transmission System and Study on Transmission Capacity Increase (By S. Yamazaki, et al.[11])

This possibility is high when these results are compared with the results of the 100-channel WDM transmission experiment with channel intervals of 10 GHz. A combination with the homodyne detection method that requires no intermediate frequency, optical frequency multiplexing can be further increased to make this system promising as a terabit optical transmission system in the future.

(3) Optical Time-Division Multiplex Transmission

Steady efforts are being made to develop optical time-division multiplexing (OTDM) technology to sharply boost the transmission capacity by time-division multiplexing very short light pulses on the time axis, although the efforts are not as active as those for WDM and OFDM. Experiments were conducted several years ago on 8 km transmission by multiplexing 4 Gb/s signals four times[14] and 100 Gb/s signal generation by multiplexing 3.125 Gb/s signals 32 times.[15]

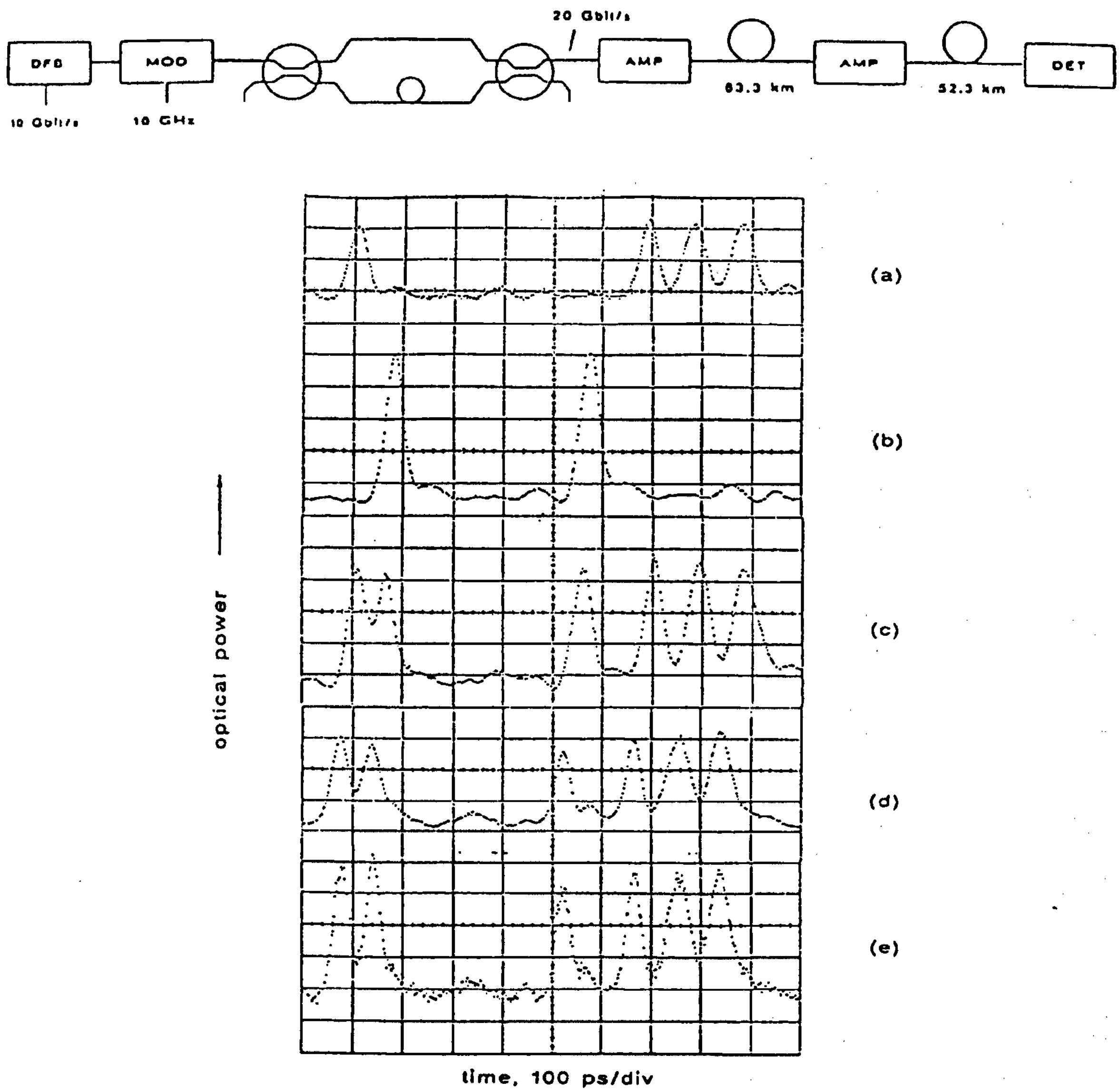

Figure 1.5.2.8. Configuration of Experimental 20 Gb/s OTDM Transmission System and Optical Pulse Waveforms (By B. Wedding and T. Pfeiffer[16])

Figure 1.5.2.8 is a recently reported example. It shows the configuration of an experimental 20 Gb/s OTDM transmission system double-multiplexing 10 Gb/s signals and waveforms at each section.[16] An external modulator turns 10 Gb/s

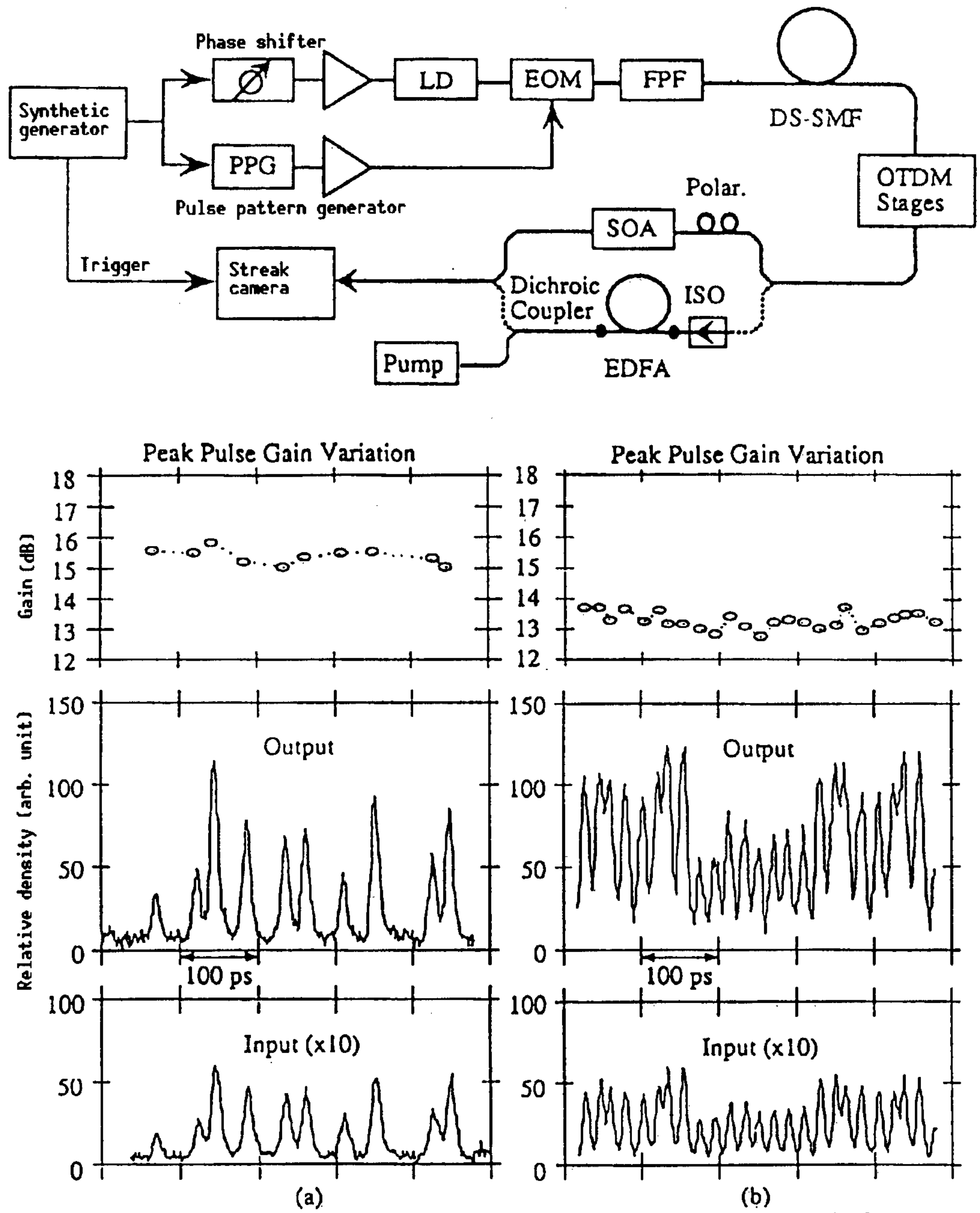

Figure 1.5.2.9. System for Experiments on Optical Amplifier's Response to Very Short Optical Pulses and Response Characteristics (By H. Izadpanah, et al.[17])

signals to short pulses, which are then mixed with delayed pulse signals by an optical coupler for multiplexing into 20 Gb/s signals. Output is boosted by an erbium-doped optical fiber amplifier for a 115.6 km transmission experiment with an optical fiber amplifier installed midway. The figure's (a) and (b) show input pulse waveforms of the channels and (c) the mixed-pulse waveform. Comparison of (c), (d), and (e) with the initial two-bit pulse waveform shows

that pulse compression takes place, with separation between pulses becoming gradually clearer. Although noise analysis and encoding error rate assessment remain as issues to be solved in the future, the advent of the optical fiber amplifier has made OFDM transmission more attractive for superhigh-speed, large-capacity transmission. In this context, the optical fiber amplifier's response characteristics to short pulses is also an important issue that must be studied. Figure 1.5.2.9 shows the configuration of a system for experiments on the optical amplifier's response to very short light pulses and the results of 50 Gb/s (a) and 100 Gb/s (b) experiments.[17] The short pulse pattern generation method is basically the same as that explained in Figure 1.5.2.8. First, the DFB laser is gain-switched and the generated pulses are shaped by a spectral filter to generate 3.2 Gb/s standard short-pulses with a pulse width of 9.8 ps. These pulses are multiplexed by a multistage OTDM system to obtain 12.5, 25, 50, and 100 Gb/s test patterns. The figure's (a) and (b) show the optical fiber amplifier's 50 Gb/s and 100 Gb/s response waveforms observed by using these test patterns. As shown, slight pulse compression takes place, but its precise mechanism is not necessarily clear. But at either transmission speed, gain fluctuations against the pulse peak is within ±0.5 dB, indicating the optical fiber amplifier is usable as an optical amplifier for at least up to 100 Gb/s transmission of very short light pulses.

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Future Trend in Materials, Device Sectors

926C1015F Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 p 192

[Text] **2.2.4 Future Trend**

The subjects taken up for the trend survey in the three years from FY89 are nonlinear optical materials and recording media in the materials sector and light emitting elements, space optical devices, optical integrated devices, display devices, light receiving devices, surface-processing optical devices, and microoptics in the device sector.

In the optical information processing field, R&D efforts will continue with higher density of information and higher speeds in processing as key words. Under the circumstances, efforts to make light sources smaller, increase their output and make wavelengths shorter will make steady progress. Various composite elements, now in the R&D stage, will enter the practical use phase, being selected in the feasibility study stage in the development of information processing equipment. R&D of materials and devices, now conducted as seeds rather than from needs, is also included in the series of surveys. We hope its exposure to developers of equipment will give birth to new equipment and concepts. (Uematsu)

Future Trends: SLM, Optical Computing

926C1015G Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 211-212

[Text] **2.3.4 Future Trend**

Research to experimentally verify devices has increased in the past several years. This looks like a sign that efforts are being made toward practical use. The SLM is indispensable to space-domain parallel processing and liquid crystal and other methods are under study. Research also started on peripheral technologies and optical computing is becoming more realistic. The neural network in particular seems to be ahead of other technologies toward practical use because the objectives of its processing are relatively clear. An SLM with higher performance will be developed in the future, marking a big step toward practical optical computing. However, it will be necessary to fully understand user needs before that.

Wavelength-domain parallel processing is a method that effectively uses the characteristics of light. Some architecture aspects have yet to be established, but there will be rapid progress in the optical conversion and memory fields.

The Ministry of International Trade and Industry (MITI) plans to create a committee to study the development of the sixth-generation computer, which includes optical computer technology. People put much hope in progress in optical computing and efforts will be even more necessary to improve technology in order to put it to practical use.

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Curvature Polygon Mirror, Plastic Scanning Lens, Multiple Beams

926C1015H Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 250-251

[Text] **(b) Recent Trend**

(i) Galvanomirror

Galvanomirrors are usually used only in low-speed machines and for special purposes such as secondary scanning. Galvanomirrors consisting of a mirror, coil, and torsion spring have recently been test-fabricated, using a processed quartz crystal wafer, photolithography, and quartz crystal anisotropic etching technology.[6]

(ii) Visible Lasers[7]

Shortening laser wavelengths is desirable for higher speeds and higher density because they can raise write density and increase spectral sensitivity of photosensitive substances, InGaAlP semiconductor lasers with wavelengths of 670~680 nm have been test-manufactured. Efforts are being made to improve reliability and increase output.

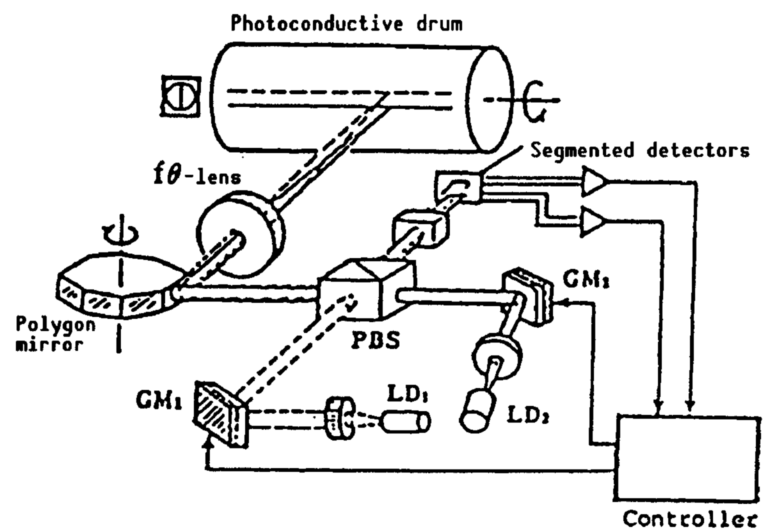

Figure 2.5.2.4. Multibeam Semiconductor Laser Scanning Optical System

(iii) Multiple Beams[8]

The number of polygon revolutions poses a problem in increasing printer speeds. To solve this problem, multiple beams have to be used in scanning. There are two ways of accomplishing this: using a semiconductor laser array[9,10] or using multiple discrete lasers.[8,11] As laser intervals are wide at around 100 μm, the former method requires optical measures to offset that. If the

semiconductor laser's faying surface is arranged in the secondary scanning direction as usual, there will be a gap of several millimeters on the photoconductor. Therefore, attempts are being made to incline the surface slightly toward the primary scanning direction. The latter method involves difficulties in maintaining the mutual positions of the semiconductor lasers. Figure 2.5.2.4 shows an example of servo position control.

(iv) Curvature Polygon Mirror

A polygon mirror usually has a flat surface. Giving curvature to this flat mirror is being attempted to increase flexibility from the viewpoint of reducing the cost and size of the optical system.

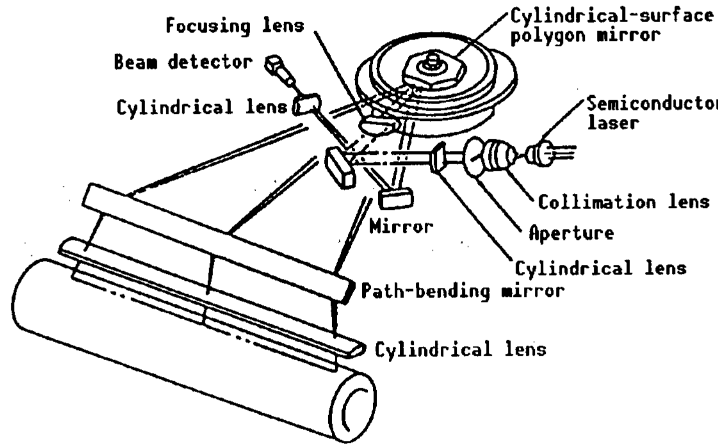

Figure 2.5.2.5. Example of Curvature Polygon Use (By Sakuma[13])

Such moves include adding to the polygon reflector shape the $f\theta$ compensation function to make uniform the spot's speed of travel on the photoconductor[12] and the adoption of the post-object structure in which the focusing lens is located between the polygon mirror and the collimator lens and imaging surface compensation is done by making the polygon reflector surface a cylindrical convex. An example of the latter is shown in Figure 2.5.2.5. The $f\theta$ characteristics are electrically corrected.

(v) Plastic Scanning Lens

The scanning lens is increasingly made of plastics in order to make the fq lens wider angle, anamorphic, and low cost. The use of plastics makes it easier to give lenses aspherical or anamorphic shapes. Lenses with a modified cylindrical surface are mass-produced. In such lenses, the imaging surface curve in the secondary scanning direction, which cannot be corrected in conventional cylindrical lenses, is well corrected.[13]

(vi) Hologram Scanner

Hologram scanners are used in bar code readers. For use in laser printers, they are required to have no bending in scanning lines, small aberrations stemming from laser wavelength changes, and no deterioration in scanning performance arising from disk surface vibrations.

Hologram scanners designed for use in laser printers have been announced.[15,16]

Features, Development Trends of LC Light Bulbs

926C1015I Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 271-275

[Text] **2.6.2 Light Bulb**

(1) Light Bulb Characteristics

Recent development efforts center on ferroelectric liquid crystal light bulbs designed for optical information processing. Their features, development trend, and future outlook will be explained below. The basic structure of a liquid crystal light bulb is shown in Figure 2.6.2.1.[1] It consists of an optical dielectric sandwiched by optical glass supporters onto which ITO transparent electrodes are evaporated, dielectric mirror, and liquid crystal layer. The write beam lowers the optical dielectric layer impedance to impress a voltage on the liquid crystal and the polarization surface of projected light is rotated. When seen through this light, the section where the polarization surface has rotated looks bright. Hughes Aircraft applied this principle to a projector, which is shown in Figure 2.6.2.2.[1] Writing is done by a cathode-ray tube (CRT) and reading by the strong light of a xenon lamp, realizing a projector far brighter than a conventional projector using a simple CRT. In this projector, the polarizing beam splitter polarizes xenon light and changes the voltage impressed on the liquid crystal according to CRT brightness to pass only light whose polarization surface has rotated. It uses twisted nematic (TN) liquid crystal which permits gray scale display.

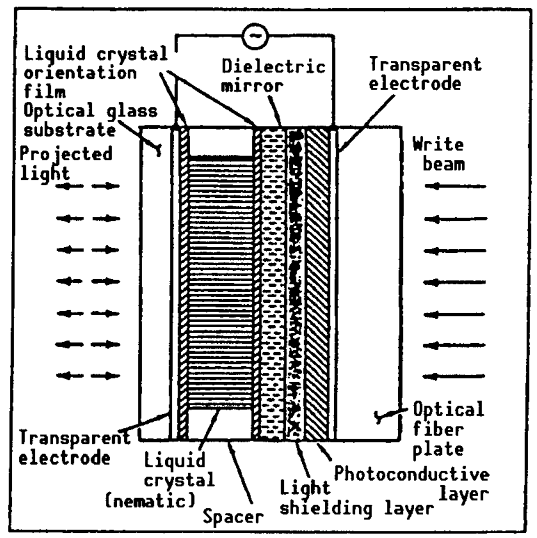

Figure 2.6.2.1. Light Bulb Structure (By Wakatsuki[1])

Light bulbs must be high speed and have good resolution and two-value memory characteristics to be used in optical information processing, particularly optical computers. The ferroelectric liquid crystal light bulb was developed

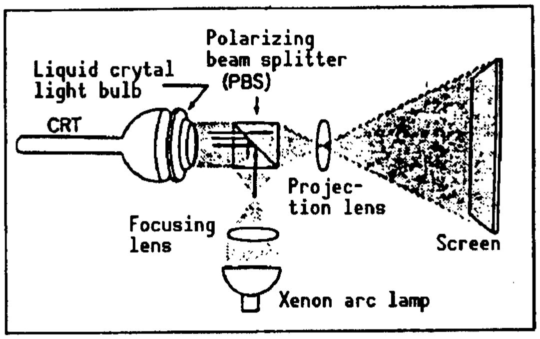

Figure 2.6.2.2. Basic Structure of Projector (By Wakatsuki[1])

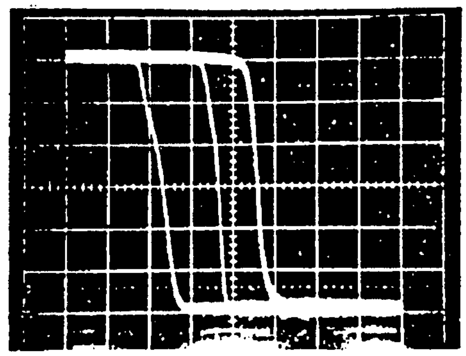

Figure 2.6.2.3. Bistable Hysteresis of Ferroelectric Liquid Crystal Light Bulb (Vertical axis: reflectivity rate; horizontal axis: impressed voltage) (By Iwaki[2])

to satisfy these requirements. The response speed is determined by the optical address time (the time from the irradiation of the write beam to the fall of photoconductor impedance), rise response time (the time from the impression of a voltage on the liquid crystal to its operation), processing time and fall response time (the time until the liquid crystal stops operation) as well as the materials and thickness of the photoconductor, voltage applied to the liquid crystal, and the orientation of the crystal.

Table 2.6.2.1. Comparison of TN Liquid Crystal and Ferroelectric Liquid Crystal Light Bulbs (By Iwaki[2])

	Device	Active size length or diameter (mm)	Resolution at 50% MTF (lp/mm)	Cycle time (ms)	Optical switching energy* (pJ)
TN liquid crystal	Hughes LCLV	25.00	16.00	100.000	50.00
	Hoechst Celanese	40.00	38.00	25.000	36.00
	a-Si : H/nematic	38.00	>35.00	100.000	2.00
	a-Si/nematic	25.00	5.00	1.400	2.50
Ferro-electric liquid crystal	a-Si/FLC	40.00	28.00	0.500	0.20
	a-Si : H/FLC	10.0	38.00	0.300	0.11
	a-Si : H/FLC (LAPS)	(25×30)	>100	0.800	0.03
	TFT-LCLV	(40×40)	330 μm□	8.000	—
	FLC-SLM	20	>20	>0.1	6.25
	BSO-SSFLC	—	—	>0.1	0.008

* Optical switching energy per bit ≡ intensity × [write-time/(2 × resolution)^2].

Compared with the TN liquid crystal, the ferroelectric liquid crystal is one to three orders of magnitude faster as shown in the cycle time column of Table 2.6.2.1. Resolution varies from similar to three times better and some have resolution of 100 lines/mm. The ferroelectric light bulb has bistable hysteresis between the driving voltage and light reflectivity because there are only two ferroelectric liquid crystal orientations. This is shown in Figure 2.6.2.3.[2]

(2) Light Bulb Development Trend

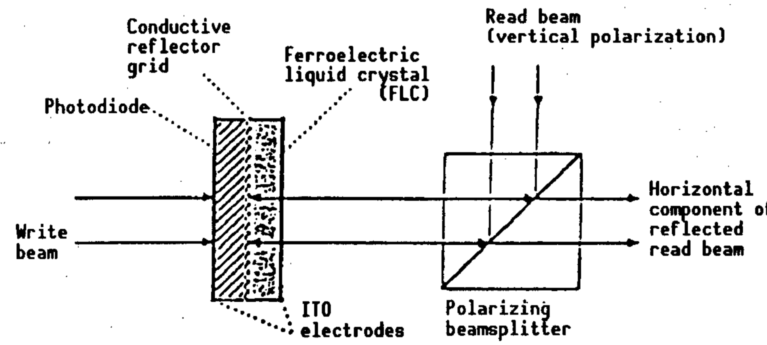

Figure 2.6.2.4. Structure of Ferroelectric Liquid Crystal Light Bulb With Conductive Grid Electrode (By Iwaki[2])

Research on ferroelectric liquid crystal light bulbs was launched in 1986 by Clark of Colorado University and Armitage of Lockheed. At that time, they used bismuth silicate single crystal ($Bi_{12}SiO_{20}$) as the photoconductor, but the results were not good. They tried various materials and obtained resolution of more than 10 lines/mm with single-crystal Si. There is a report on a thin-film transistor (TFT)-driven ferroelectric liquid crystal light bulb using amorphous Si as the photoconductor.[1] It has 120 x 120 pixel arrangements and optical response speed of 125 Hz. The speed is not fast, but it can be made faster by optimizing the R-C constant. There is also a report on a light bulb using conductive grid electrodes, which is shown in Figure 2.6.2.4.[2] Writing is done by irradiating the write beam while applying a forward voltage between the conductive grid electrode and ITO electrodes on the write surface, and a recorded image is erased electrically by applying a reverse voltage. Only a slight voltage is applied to the ferroelectric liquid crystal, which is either dark or bright, and memory is gradually erased by that slight voltage. Therefore, this light bulb requires cyclic sequential writing.

(3) Application Examples and Future Trend

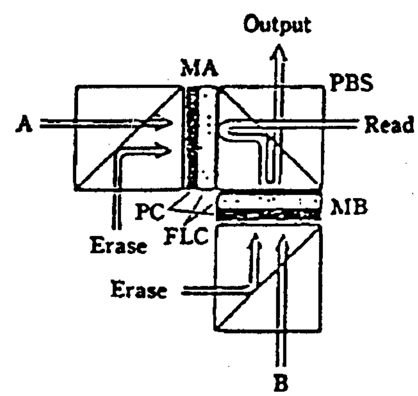

Figure 2.6.2.5. Use in Digital Optical Adding/Subtracting Module (By Iwaki[2])

The ferroelectric liquid crystal light bulb is still under development and no bulb of that kind has been commercialized. The reported application field is the optical computer sector. One such application is its use as parallel-operation adding processors for digital optical operation. Figure 2.6.2.5[2] shows an adding processor module for parallel processing. It consists of two ferroelectric liquid crystal light bulbs and three polarizing beam splitters (PBS). The polarization of the read beam at the time when A and B inputs are both ON becomes the same as that of input at the two liquid crystal light bulbs and thus the read beam comes out via the PBS, representing ON. As it is OFF otherwise, this constitutes AND logic. If the input state is reversed, it becomes NAND logic. As the ferroelectric liquid crystal has memory, the write state is maintained in operation, but the memory can be initialized by an erasing pulse and the erasing beam.

Another application example is an optical memory. It is shown in Figure 2.6.2.6[2] where P1 and P2 are ferroelectric liquid crystal light bulbs. D at the lower left is input and either one of the two polarization states can be input. In the H polarization state, the beam is reflected by the polarizing beam splitter and becomes input to P1. It becomes input to P2 in the other polarization state. That is, reversed information is stored in the two ferroelectric liquid crystal light bulbs. This system constitutes an optical flip-flop circuit. From the mid-left, the read beam enters the light bulbs and output beam Q comes out. When the input beam is converted into nxm pixel data, a high-speed optical memory is created. There are reports on the use of the ferroelectric liquid crystal light bulb in an analog optical correlator. But as the bulb can handle only two values, the optical system requires a feedback mechanism, making it complex. Other applications include the bulb's use as an optical associative memory.

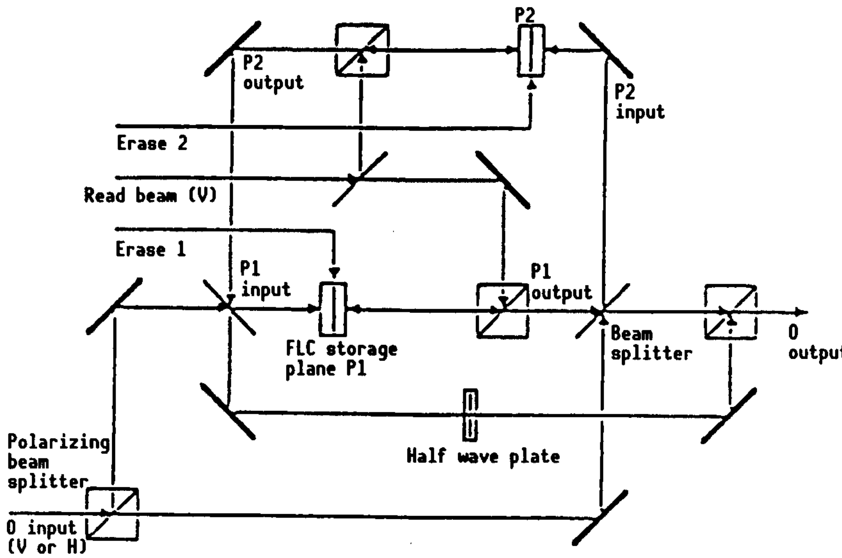

Figure 2.6.2.6. Application as Digital Parallel Optical Memory (By Iwaki[2])

The primary features of optical computing are parallel operation and the speed of light. Adequate resolution and size are necessary for parallel processing, while high-speed elements are required for effective use of the speed of light. The memory access time of existing personal computers is about 100 nanoseconds, but that of the ferroelectric liquid crystal light bulb noted here is in the millisecond order, about four orders of magnitude slower. High resolution is required to offset this. Thermal and mechanical stability is also required. Development efforts will center around this point in the future. Optical computing is still a wild dream and it is not known in which direction R&D should be carried out. Therefore, various operation methods and configurations will be proposed in the future. (Onuma)

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Future Trend in Image Display Technologies

926C1015J Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 p 292

[Text] **2.6.7 Future Trend**

Efforts to put image display technologies to practical use are making steady progress in various fields.

Various color printer systems have been developed at last and practical models have been put on the market. Further improvements in performance and reductions in prices are desired.

Speeds and resolution of light bulbs are still far from required values when they are assumed to be used in optical computers. Further R&D efforts are necessary in this sector.

There are various kinds of flat display panels. Liquid crystal technology has made remarkable progress and practical, if expensive, flat displays are commercialized for use in office automation equipment. An important issue from now will be cost reduction through improved throughput.

Interesting three-dimensional display technology trends are eye-point tracking display technology and technology to make virtual work space. These are beyond the scope of existing technology and create virtual space that follows the move of a human being. Various trials are expected to be made in the future.

Hi-Vision standardization still involves big problems and it is not clear if standardization is possible in important points. A further increase in the screen size will be called for in the future to capitalize on high definition. Active efforts are being made to develop peripheral technologies in order to apply Hi-Vision in other media.

Holographic video has made a step toward an ideal three-dimensional image that moves on a real-time basis. It could be used for output of computer graphics and others in the future. The method currently in use employs an acoustic optical modulator (AOM). As various other devices may be used in place of AOM, many trials will be made in the future. (Iwata)

Technological Progress in Excimer Lasers

926C1015K Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 299-300

[Text] **3.2 Light Source Technology Trend**

3.2.1 Excimer Laser

(1) Excimer Laser for Processing

There has been remarkable technological progress in excimer lasers for processing since the beginning of 1990. In the application sector, demand for them increased for use as light sources in the manufacture of 64 megabit dynamic random access memories (DRAMs). and for abrasion processing. This led to such progress as longer life for gas, electrodes, and switches, and higher reliability. Efforts to develop excimer lasers under the New Energy Development Organization's big "superhigh-technology processing system" project reached an intermediate point, producing such technical improvements as higher output, higher repeatability, higher efficiency, longer pulses, and longer life. These recent advances are explained below. Refer to this report for FY89 and FY90 for basic and other technologies.

(a) Higher Output

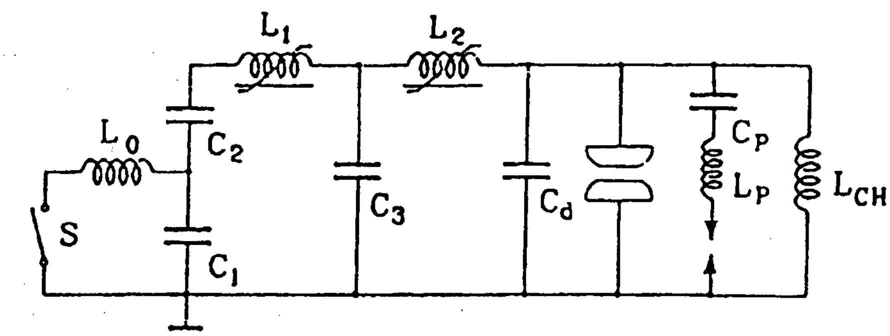

Figure 3.2.1. LC Reversal and Two-Stage Magnetic Pulse Compression Circuit

Lambda Physik recorded a momentary output of 750 W by combining ultraviolet-ray preliminary electrolytic dissociation by spark discharge and a capacity transfer circuit.[1] However, oscillation efficiency is low at 1 percent or less under this method and it is difficult to gain kilowatt-class high output. The method is thus hard to put to practical use. Bergmann, et al., of Rand Afrikaans University (South Africa) adopted

ultraviolet-ray preliminary electrolytic dissociation and a circuit (Figure 3.2.1) consisting of LC reversal and two-stage magnetic pulse compression to achieve an average output surpassing 500 W (1.6 kHz) with a KrF excimer laser.[2]

While research is continuing on conventional methods and their improvement, active efforts have also been made recently to develop a new excimer laser system. Under this system, an electric circuit consisting of a spiker circuit for starting a discharge and a sustainer circuit for energy injection supplies energy to the discharge section with high efficiency. It is marked by a long oscillation pulse time and high efficiency.

In the United States, high-output research is under way, using this combination of a spiker/sustainer circuit and X-ray preliminary electrolytic dissociation discharge. Spectra Technology has succeeded in single-pulse high-output oscillation of more than 20 J, but it has yet to achieve repeated oscillation. Under the Eureka project of Europe, efforts are being made to achieve repeated oscillation with output of 1 kW (repetition 1 kHz), using a combination with X-ray preliminary electrolytic dissociation discharge or corona preliminary electrolytic dissociation discharge. Studies by Rumoniks [phonetic] of Canada and Mitsubishi Electric Corp. of Japan are attracting attention as research on repeated oscillation. The former uses a combination of conventional ultraviolet preliminary electrolytic dissociation by spark discharge and a spiker/sustainer circuit. It has succeeded in momentary oscillation with pulse energy of 1 J and repetition of 220 Hz with an XeCl laser.[3]

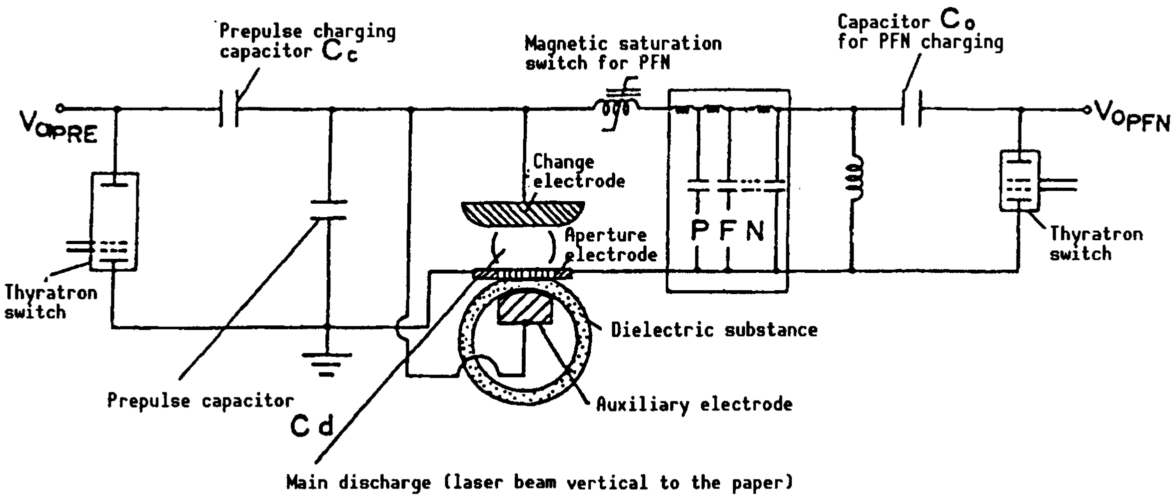

Figure 3.2.2. High-Repeatability Excimer Laser Circuitry Combining Corona Preliminary Electrolytic Dissociation Discharge and Spiker/ Sustainer Circuit

Mitsubishi Electric Corp. has achieved long-pulse high-repetition operation of 500 Hz with oscillation sustenance time of 340 ns, using an XeCl laser (Figure 3.2.2)[4,5] combining creeping corona preliminary electrolytic dissociation discharge and a spiker/sustainer circuit.[6] It has also succeeded in developing basic technology for high-efficiency, high-output excimer laser, attaining oscillation efficiency of 2.2 percent and slope efficiency (the laser output

slope against discharge input) of 4.8 percent. Photo 3.2.1 [not reproduced] shows an external view of this equipment. The characteristic point of this system is that, as shown in the voltage and current waveforms in Figure 3.2.3 [not reproduced], after switching on the spiker circuit's thyratron, the magnetic saturation switch is turned on when the prepulse voltage gets high negative electric potential, withholding the start of discharge at this point. Then the voltage shows a very sharp inverted rise of 50 kV within about 50 ns, starting a discharge with a positive, high breakdown voltage. As a result, a uniformly dispersed, stable spiker discharge can occur. This unprecedented voltage reversal and a low-inductance main discharge circuit enable high repetition operation at the spiker/sustainer circuit.

Figure 3.2.4 [not reproduced] shows the relationship between the repeated oscillation excimer laser's output per pulse and the repeating frequency.

(b) Higher Repeatability

Technology development is under way for kilohertz-class high repeatability. Under the large-scale project mentioned above, Toshiba achieved 2.5 kHz repeated oscillation for an average output of 87 W with an XeCl laser combining ultraviolet-ray preliminary electrolytic dissociation discharge and a capacity transfer circuit.[7] Higher repeatability destabilizes discharge, causing a drop in output. Mitsubishi Electric developed a semiconductor switch consisting of field effect transistor (FET) modules and succeeded in high 1.5 kHz repeated oscillation with a KrF laser.[8]

(c) Higher Efficiency

Oscillation efficiency has also been improved. Twente University of the Netherlands succeeded in obtaining pulse energy of about 100 mJ at high efficiency of 5 percent, albeit in single-pulse operation, by combining X-ray preliminary electrolytic dissociation discharge and a spiker/sustainer circuit.[9] Rumoniks developed a KrF laser system with a conventional combination of ultraviolet-ray preliminary electrolytic dissociation discharge and a capacity transfer circuit but having a main discharge circuit with smaller inductance, and achieved oscillation efficiency of 4.5 percent.

Technological Trend in Optical Energy Applications

926C1015L Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 383-391

[Text] **3.3 Technological Trend in Optical Energy Applications**

3.3.1 Microelectronics Application

(1) Excimer Laser Lithography

(a) Exposure System

(i) Outline

Steppers having a mercury vapor lamp as the exposure light source are now chiefly used as exposure equipment for the production of advanced large-scale integrated (LSI) devices like dynamic random access memories (DRAMs). A stepper allows noncontact reduction projection of a circuit pattern on the reticle onto a wafer. Since it can be used while maintaining high reticle quality, there are few transfer pattern defects. The exposure region of lenses used is limited and focusing must be carried out for each section of a wafer before exposure. This leads to little shift in focus even if there is unevenness on a wafer. An exposure system's resolution R is limited by diffraction of the exposure light. It is represented by the following equation:

$$R = k_1\lambda/NA \qquad (3.3.1(1).1)$$

where λ is the exposure light wavelength, NA is the numerical aperture of the projection lens and k_1 the process factor incorporating the resist's characteristics. As finer patterns can be transferred when λ is made smaller, efforts have long been made to shorten the exposure light wavelength. From 1990 to 1991, new steppers increasingly used the i ray (λ = 3,654 nm) instead of the g ray (λ = 436 nm) as the light source. Steppers using a KrF excimer laser with a wavelength of 248 nm have been developed in order to obtain even higher resolution than that achieved by the i ray.

Since American Telephone and Telegraph Co. (AT&T) announced a stepper with an excimer laser having a narrow oscillation spectrum for better monochromatism

and an exposure optical system whose lenses are all made of synthetic quartz, several stepper makers announced similar systems.[1-4,6,7] The current main target is the development of exposure equipment for a line width of 0.35 μm used in 64-megabit DRAMs. This report will discuss the development of excimer steppers over the last year or two.

(ii) Illumination system and Projection Lens

The excimer laser will be omitted because it is explained elsewhere in this report and the development of the illumination system and projection lenses is explained here. The illumination system must have a uniform intensity distribution over the exposure area and give a designated amount of exposure to the wafer. Since a laser's intensity distribution is not uniform, the fly eye and other optical devices are used. Nikon Corp. developed a system whose illumination unevenness is within ±2.5 percent.[2] It is required to make intensity distribution as uniform as possible while maintaining intensity of illumination as high as possible and take measures against the generation of interference fringes by the laser beam's spatial coherence. The illumination system announced by Muraki, et al., of Canon Inc. maintains the uniform intensity of illumination even when the laser beam moves relative to the illumination system by splitting the laser beam into four and reversing them and overlapping them.[7] The excimer laser's pulse energy becomes uneven, but exposure amount control precision of around ±1 percent can be obtained for exposure of more than 100 pulses by monitoring and integrating exposure pulse energy and finishing an exposure when the exposure reaches a designated value Decreasing the minimum number of pulses necessary for exposure is effective in increasing the number of wavers processed per unit/time by shortening the exposure time and extending the life of laser components. Hollman, et al., of GCA operated a movable attenuator during exposure, demonstrating that it is possible to control the exposure of 1 percent at 20 pulses.[4]

Nikon announced it will market a projection lens with nominal resolution of 0.45 μm and exposure area of 17.5 mm^2. Figure 3.3.1(1).1 shows a pattern example of a positive resist transferred by this lens. Its exposure area is large enough go allow test-fabrication of a 64M DRAM. Olson, et al., of GCA reported n the imaging performance of a stepper equipped with a projection lens with Na of 0.44 and exposure area of 21 mm in diameter.[3] It is noteworthy that using a negative resist, a linewidth of 0.25 μm can be isolated and that imaging position distortion is small at 0.02 μm in the radial direction.

(ii) Alignment

It has been considered possible to improve alignment accuracy if it is possible to measure a shift in the relative positions of the reticle and wafer via a projection lens made only of quartz crystal. But this kind of projection lens has strong chromatic aberration, making it difficult to focus light near visible rays used for alignment. Therefore, most excimer laser steppers adopt the off-axis system which has an alignment measuring system outside the projection lens.[1,2,4] The problem involved in this system is the stabilization of the so-called baseline, or the distance between the projection lens and the alignment measuring system. Wittekoek, et al., of ASM unveiled a system that

carries out alignment by the through-the-lens (TTL) method.[6] An He-Ne laser beam (wavelength 633 nm) is introduced to the iris section of the projection lens from its side and ± primary light from the lattice-like alignment mark on the wafer is focused on the reticle by a lens whose chromatic aberration is corrected. Alignment precision of 0.1 μm at $X \pm 3\sigma$ is achieved over the entire exposure area. It is good enough to be used for the manufacture of LSIs with a linewidth of 0.35 μm.

FH — EX (t : 0.5 μm)

SOFTBAKE	:	90°C / 60 SEC
EXPOSURE	:	NIKON New Version Lens
PEB	:	110°C / 60 SEC
DEVELOPMENT	:	TMAH / 60 SEC / PUDDLE

0.30 μmL/S

Figure 3.3.1(1).1. Postive Resist Pattern

(iv) Pellicle

The reticle is increasingly protected by a pellicle stretched on a frame as circuits may become defective if dust sticks to the reticle. In an endurance test, a pellicle made by E.I. du Pont de Nemours Co. proved to be free from deterioration even when energy equivalent to exposure by stepper for 10 weeks is applied to it.[5] This means the removal of one of the hurdles to the use of excimer steppers for those who believe a pellicle is indispensable to LSI mass production with steppers.

(v) Future Moves

Achievements by several stepper developing groups show that element technologies for KrF excimer steppers for 0.35 μm-rule devices have almost been completed. Development energies will now be devoted to enhancing system completion in order to give all performances to one exposure system. The next development target is a lithographic system for 0.25 μm-rule devices. One light source candidate is the ArF excimer laser with a wavelength of 193 nm. (Tanimoto).

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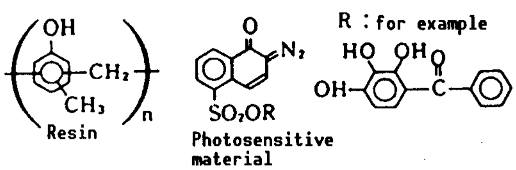
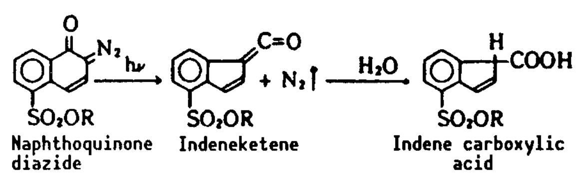
(b) Lithography

The current status and problems of excimer laser lithography using the KrF laser as the light source will be explained here, centering on resist materials and process technology.



(a)



(b)

Figure 3.3.1(1).2. Novolac Positive Resist

(i) Resist Materials

(A) Quinonediazide-Novolac Positive Resist

Attempts are being made to use quinonediazide-novolac positive resists (hereinafter called novolac positive resists), fully developed and used extensively in conventional g-/i-ray exposure, in excimer laser lithography.

As shown in Figure 3.3.1(1).2, a novolac positive resist uses naphthoquinone-diazide-sulfonic acid ester as the photosensitive material and novolac as the resin. The novolac resin is originally water-soluble, but naphthoquinone-

diazide works as an agent preventing dissolution and it is not dissolved by an alkaline developer. When an ultraviolet ray is irradiated, a naphthoquinone-diazide reacts with water via indeneketene and changes into indene carboxylic acid, losing the ability to prevent dissolution, and the novolac resin becomes soluble in an alkaline developer, forming patterns.[1]

However, both the photosensitive material and novolac resin highly absorb the excimer laser beam and only several percent of the light reaches the bottom of the resist when the resist thickness is 1 μm. Therefore, underdevelopment occurs at the resist bottom which is underexposed and overdevelopment occurs at the resist top, causing a decrease in the resist thickness and a deterioration in the resist profile. Absorptivity of the photosensitive material stems from naphthoquinone-diazide and the benzene ring of benzophenone shown in Figure 3.3.1(1).2. Attempts are being made to change the esterification rate and lower absorptivity by using a non-benzophenone material in order to optimize the resist for use in excimer laser exposure.

Figure 3.3.1(1).3 shows resist patterns made by an 0.7 μm thick novolac positive resist and an excimer laser stepper with a numerical aperture of 0.42. The minimum line width is 0.35 μm. But the resist thickness cannot be over 1 μm for its light absorption and layers where novolac positive resists can be used are limited.[2]

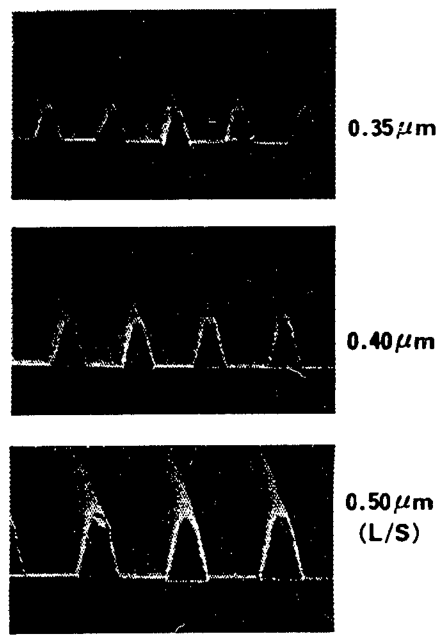


Figure 3.3.1(1).3. Resist Patterns Made With Novolac Positive Resist

(B) Chemical Amplification Resist

As there are limits to improvement of novolac positive resists, chemical amplification resists are now attracting attention.[3,4] They use an acid generating agent like onium salt as the photosensitive material and heating before development promotes the resin's cross-linking and dissolution with the acid working as a catalyzer, and a change indissolubility to the developer forms a pattern. Even a tiny amount of acid generated by exposure causes many reactions, making it possible to achieve very high sensitivity. Thus the addition of an acid generating magnet, which causes light absorption, can be small, making it possible to increase transmittance.

As Figure 3.3.1(1).4 shows, the best resist at present is the three-component negative chemical amplification resist that uses polyvinyl phenol as the resin, a halide as the acid generating magnet, and melamine derivative as the cross-linking agent.[4] Figure 3.3.1(1).5 shows resist patterns when the resist thickness is 1 μm. The 0.3 μm pattern is well shaped and sensitivity is very high at 30 mJ/cm^2. However, in addition to insufficient etching resistance, there are such problems as low fidelity of pattern sizes against mask sizes, a phenomenon peculiar to negative resists, vulnerability to optical proximity

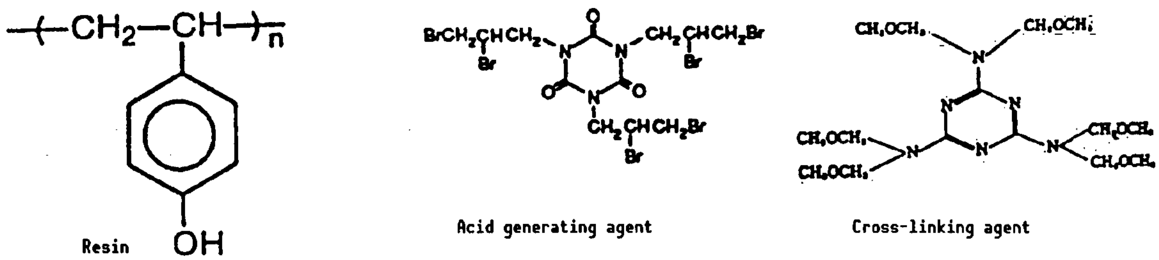


Figure 3.3.1(1).4. Three-Component Negative Chemical Amplification Resist

effect, bridging between resist patterns and a change in the resists shape according to the underlying substrate.

Two-component positive resists are well known, though still in a laboratory phase.[3] The hydroxy of polyvinyl phenol is protected by a protective radical like t-butoxycarbonyl and an acid generated by exposure removes the protective radical, reviving the hydroxyl to make the resist soluble in an alkaline developer.

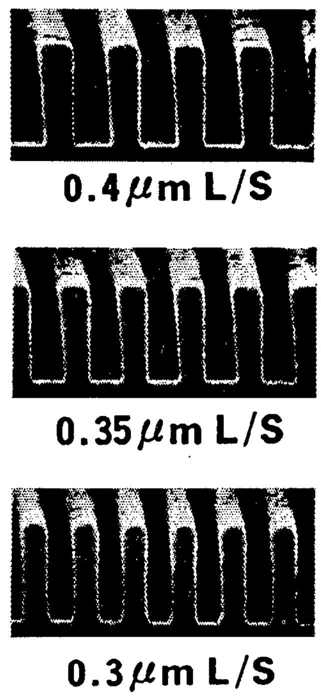


Figure 3.3.1(1).5. Resist Patterns Made With Chemical Amplification Resist

(ii) Resist Process

As explained above, the currently available resist materials involve many problems. Thus, a resist process in which these problems are offset by a multilayer resist structure to gain high resolution becomes necessary.

(A) Multilayer Resist Process

The surest multilayer resist process is the three-layer resist process shown in Figure 3.3.1(1).6. The three-layer resist consists of, from the bottom, a planarization layer that planarizes the substrate and prevents reflection, a polymethyl solixane (SOG) intermediate layer of around 0.2 μm in thickness and the top-layer resist.[5] Each layer is pattern-transferred by reactive ion etching (RIE) that causes no undercutting, generating no size differences between the top and bottom of a gap. As the intermediate layer is thin and SOG which allows RIE relatively easily, it is possible to help resists with poor etching resistance and shapes.

Figure 3.3.1(1).7 shows a resist pattern made by the three-layer resist process using a novolac positive resist. It is an 0.3 μm-line-and-space pattern with a very high aspect ratio.

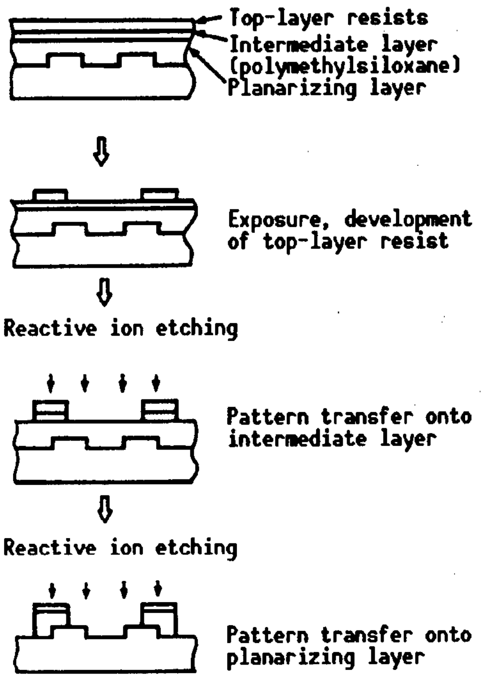


Figure 3.3.1(1).6. Three-Layer Resist Process

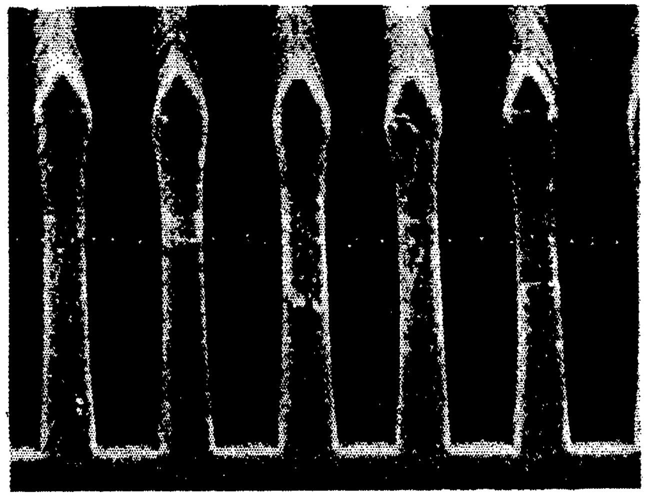


Figure 3.3.1(1).7. Resist Pattern by Three-Layer Resist Process

(B) Alkaline Processing

Resist processes which increases resolution of novolac positive resist are also effective at present. As an example, lateral and surface modification for enhancing resist contrast (LASER) is briefly explained below.

The LASER process is shown in Figure 3.3.1(1).8.[2,6] After resist coating and baking, the resist is dipped into a tetramethyl ammonium hydro-oxide (TMAH) alkaline solution to form a layer which cannot be dissolved by the developer on the surface layer of the resist (alkaline processing). In the first development after exposure, developing is stopped halfway before the pattern is thoroughly made. The second development is done after rinsing and drying, completing patterning.

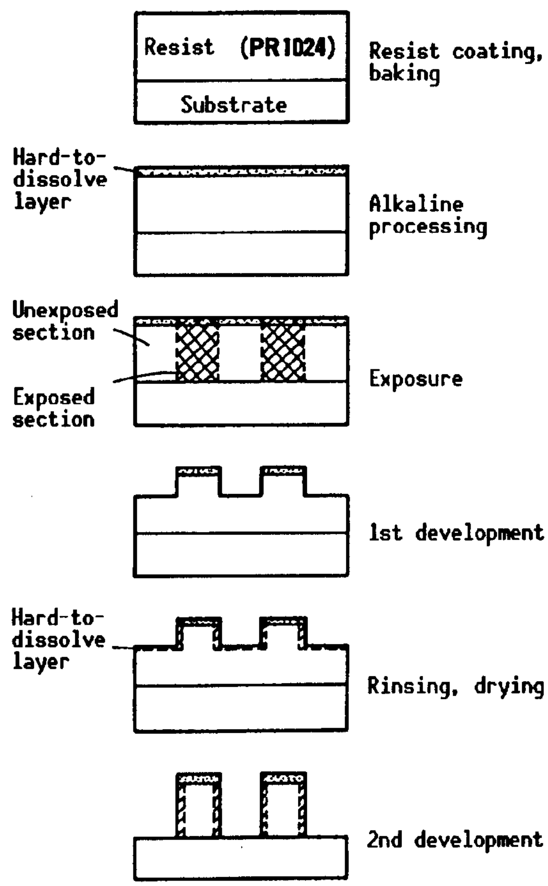


Figure 3.3.1(1).8. LASER Process

Resist patterns made by LASER are shown in Figure 3.3.1(1).9. Compared with the patterns made by the conventional process shown in Figure 3.3.1(1).3, the LASER patterns show improved resist

profiles. The sharper profiles were made possible by the alkaline of the resist surface layer and the deposition of a hard-to-dissolve layer also on the sidewalls of the patterns when the first development is stopped, which allows the preservation of the resist profile during the second development. It is presumed from ESCA and infrared spectral analysis that such a layer is deposited because the soluble component of the novolac resin is extracted through reaction with rinsing water, increasing the density of the photosensitive radical as a dissolution preventing agent.[6]

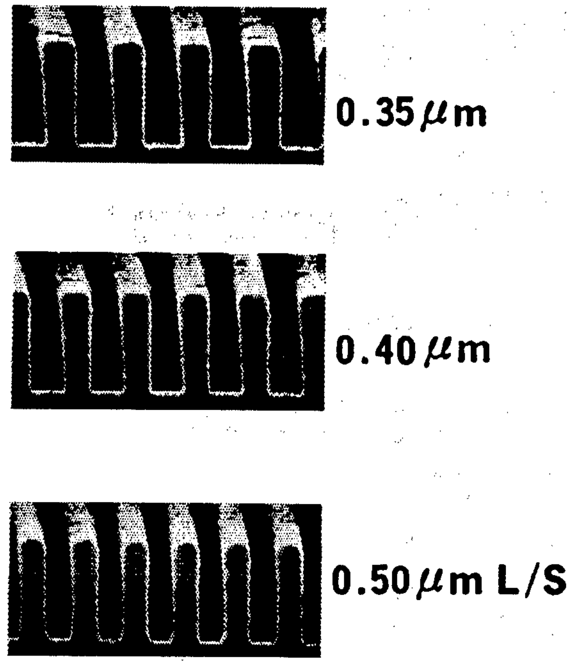


Figure 3.3.1(1).9. Resist Patterns Made by LASER

(iii) Future Outlook

This section thus dealt with the current status and problems of excimer laser lithography and explained that test fabrication of 0.3 μm-rule patterns is possible with the current technology. The key to the practical use of excimer laser lithography is perfecting resist materials as well as excimer laser equipment. The advent of the chemical amplification resist marked a big advance on the materials front. With the future development of a high-performance resist matching the novolac positive resist in g-/i-ray exposure, KrF excimer laser exposure will be put to practical use, using single-layer resists without the adoption of the resist process. But the development of a new process will be indispensable to the use of ArF_1F_2 excimer laser exposure in the future because the absorption of all high-molecular materials increases, limiting exposure to the very thin layer of the resist surface. Nonetheless, excimer laser lithography is no doubt the next-generation lithographic technology and researchers will seek every possibility to commercialize the technology. (Nakase)

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Future Outlook for Optical Etching

926C1015M Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 400-401

[Text] **(d) Future Outlook of Optical Etching**

This section discussed pattern etching on SiO_2, SiC, Teflon, and other materials on which optical etching is difficult. Conditions for the optical process are that the etchant and the material to be etched should absorb excitation light and that binding/unbinding energy of the material's atoms should be smaller than the excitation light's photon energy. But even if the conditions are met, chemical reactions of an intermediate product generated by photolysis may help etching. There may be methods concurrently using laser beams with multiple wavelengths or an excitation source other than light. It will become necessary to consider etching processes that take these composite reactions into consideration.

The etching industry also has many social problems. As the Montreal Protocol says it is a dominant view that chlorofluorocarbon is blamed for the depletion of the ozone layer, and the use of not only chlorofluorocarbon but also chloride gases is now restricted. This makes etching difficult. Chloride gases have been suitable etchants because they are easily degraded by light. If the industry thinks, "If Cl can no longer be used, then we can switch to F," F will follow the same destiny as Cl in several years. It will be too late to do something after that. We have to do integrated research and development on etching processes, including the recovery of waste gases, based on the recognition that "etching cannot exist without halogen gas." The etching industry will undergo an ordeal next fiscal year. (Murahara)

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Excimer Laser Processing, Laser Welding, Surface Reforming

926C1015N Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 423-433

[Text] **(c) Future Outlook of Excimer Laser Processing**

Although they are not discussed in detail here, there are promising aspects of future developments in basic research: surface layer improvement of high-film,[5] synthesis of high-quality high-temperature superconducting thin film using excimer laser physical vapor deposition (PVD),[6] high-speed three-dimensional shaping using photohardening resin,[7] bone shaping and processing using tapered optical fibers for transmission,[4] and bioprocessing applications. It is expected that research will veer away from existing photochemistry, creating a new field where nonlinearity and locality of the excimer laser's high luminance is sufficiently utilized. Such research will be encouraged by such national projects as the "superhigh-technology processing system" project of the New Energy Development Organization (NEDO), and the "extremely slight conversion" project of the Research Development Corporation of Japan as well as research efforts by industrial circles in nanometer and picometer processing technology. (Nagai)

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(2) CO_2 Laser Processing

(a) CO_2 Laser Application Fields

It has been many years since people started using CO_2 lasers for processing purposes. The spread of CO_2 laser processing machines has been particularly remarkable in the past several years and sales are estimated to reach 1,120 units worth ¥36.8 billion in 1990, and 1,300 units worth ¥42 billion in 1991.[1] A breakdown by application shows those for shearing account for 85 percent, those for welding about 8 percent, and those for surface reforming a very small percentage. The ratio has remained unchanged over the past several years. But many research reports cover welding and surface reforming applications and use in these fields is expected to increase in the future.

Job shops are said to be contributing much to the wide spread of CO_2 laser machines for shearing purposes.[2] These shops are spreading to provincial areas due to spiraling land prices and labor shortages in urban areas. Against this background, research societies for laser processing are increasingly being set up in provincial cities with research activities are being stepped up. Seminars and exhibitions are held at various places and new processing systems and technologies are reported there.

(b) Processing Machine and Technology Trends

(i) Shearing and Boring

In the shearing and boring field, which accounts for a majority of CO_2 laser processing applications, widely-used machines are general-purpose two-dimensional processing machines for shape cutting of fixed-length sheets. In order to do shape cutting by leading CO_2 lasers to the processing point, either the laser beam or the work to be processed must be moved, and various laser processing machines using different moving methods are produced. Typical examples are shown in Photos 3.3.2(2).1 and 3.3.2(2).2. In the machine shown in Photo 3.3.2(2).1, the work moves two-dimensionally against a fixed laser beam, while in the unit shown in Photo 3.3.2(2).2, the laser beam moves along one axis and the work moves along another axis that crosses the other at right angles.

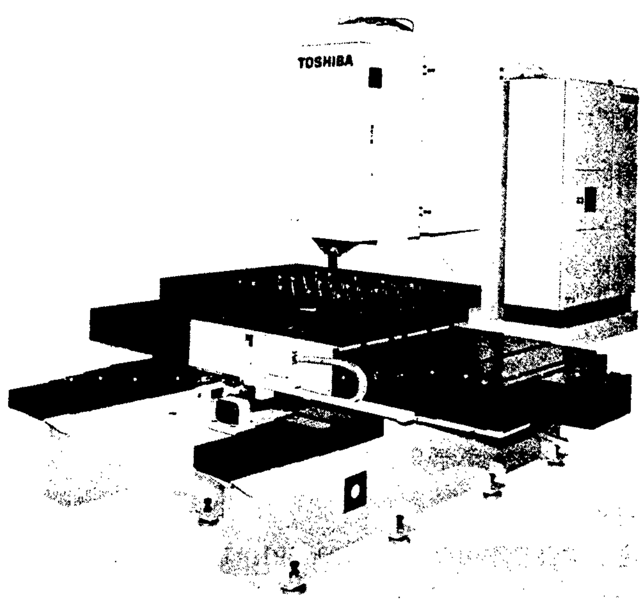

Photo 3.3.2(2).1. Example of CO_2 Laser Processing Machine (from Toshiba Catalog)

Such laser processing machines have a processing speed of around 15 m/minute and high positioning accuracy of up to several microns. But actual processing speeds and precision depend on materials and work thickness.

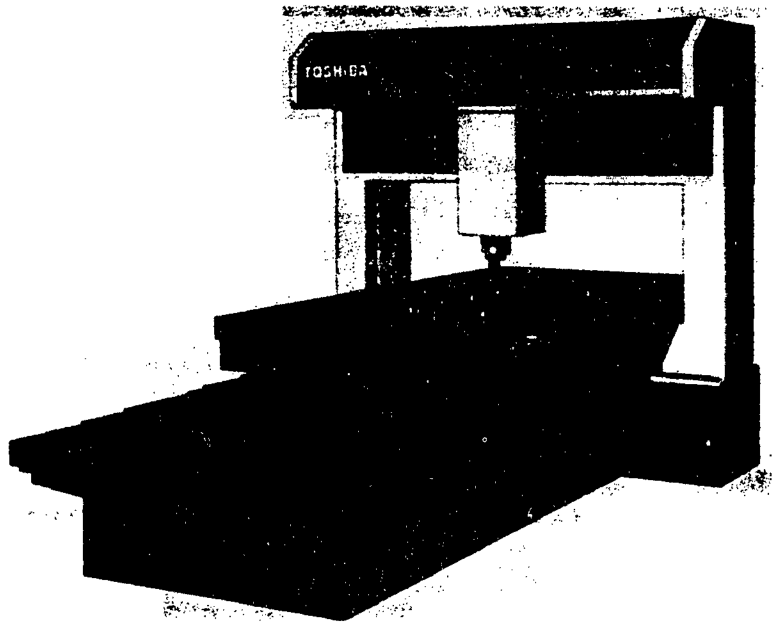

Photo 3.3.2(2).2. Example of CO_2 Laser Processing Machine (From Toshiba catalog)

These laser processing machines mainly use 1 kW-class oscillators and cut soft-steel work with a thickness of up to around 6 mm. But in line with diversifying cutting needs, efforts are being made to increase speeds and accuracy and improve cutting technology and processing equipment to cut thicker materials and high-reflectivity materials like aluminum and copper.

To meet the demand for higher speeds and higher precision, the use of laser processing machines equipped with 32-bit numerical control (NC) devices has increased. Active research on shortening the piercing time is also being carried out to achieve higher processing speeds, and it is reported that pulses with high peak values are effective to that end.[3] There are reports that the speed of laser cutting machines has increased to match the speed of turret punch presses, but turret punch presses are still faster in continuously boring simple round holes. Composite processing combining a turret punch press and laser processing machine is thus effective for processing products including many such shapes, and composite processing machines are actually widely spread.

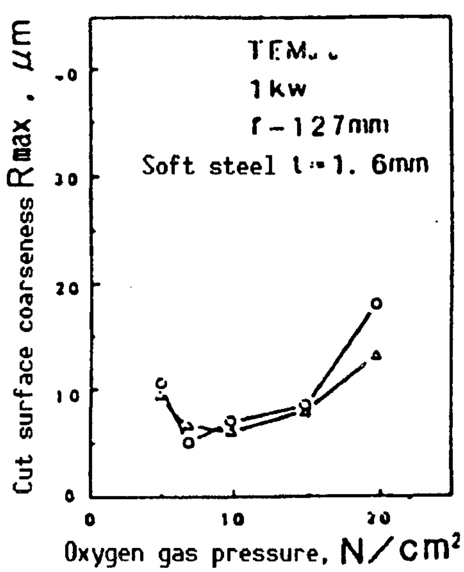

Figure 3.3.2(2).1. Dependence of Cut Surface Coarseness on Oxygen Gas Pressure (By Miyazaki[4])

The roughness of the cut surface depends on the type and pressure of assist gas (Figure 3.3.2(2).1) and also is due in large part to the oscillator's power ripple, and their improvements have been reported.[4] The cutting precision of a CO_2 laser is generally said to be around 50 μm, but lasers with precision of about 10 μm are now used in actual processing lines.[5] Photo 3.3.2(2).3 shows nibs whose slits

were processed by a CO_2 laser. Positioning accuracy was 0.1 mm as against 0.4 mm-thick stainless steel nibs. Photo 3.3.2(2).4 shows an external view of the processing machine. For high-precision processing, the processing equipment should naturally be highly accurate. But that is not enough and it is reported that special jigs need to be developed.

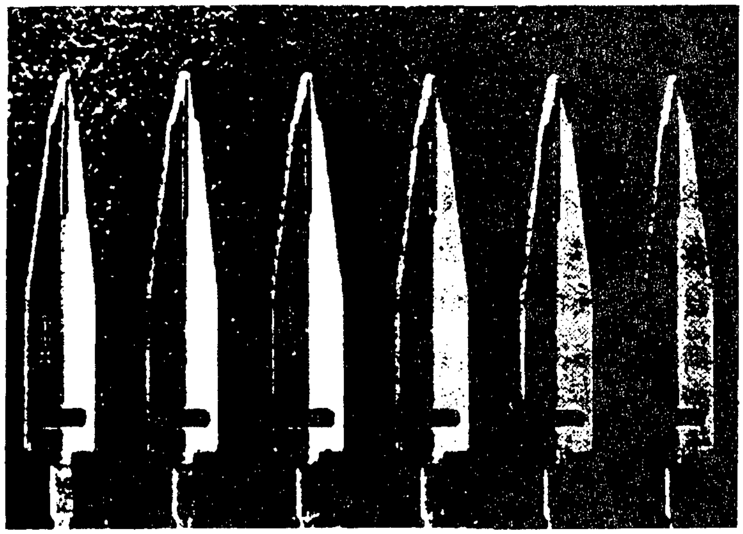

Photo 3.3.2(2).3. Example of Nib Processing (By Matsushita[5])

CO_2 lasers were able to cut soft steel with a thickness of up to some 6 mm, but now demand is rising for laser processing of steel with a thickness of more than 10 mm. Accordingly, higher output is required of laser oscillators and 2 kW-class oscillators have come into use. Photo 3.3.2(2).5 shows a 2 kW-class oscillator. High-output oscillators of 5 kW and 10 kW classes are practically used in Japan, but they are multimode or ring mode models using unstable resonators and not suitable for cutting purposes. The output of CO_2 laser processing machines for cutting applications is currently up to 2 kW and it is reported that such lasers can cut soft steel sheets 16~19 mm thick.

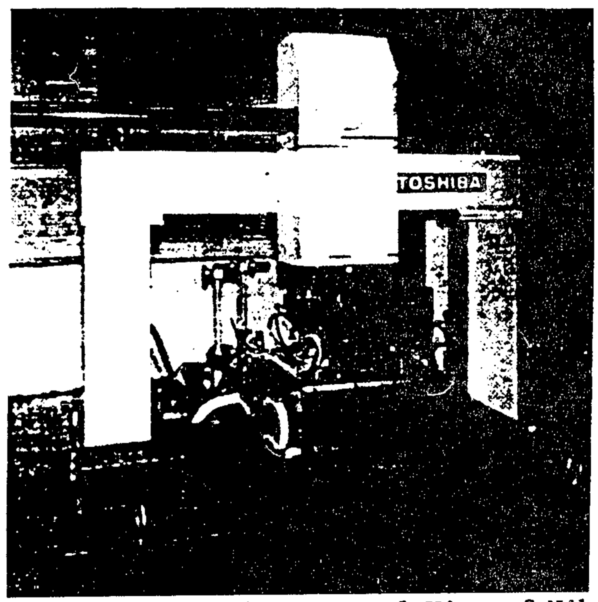

Photo 3.3.2(2).4. External View of Nib Processing Machine (By Matsushita[5])

General-purpose processing machines are widely used for cutting sheets 6 mm or less thick and systems that automatically feed in and out work sheets are produced. Figure 3.3.2(2).2 shows an example of work classification. Automatic feed out of work can be achieved relatively easily by using microjoints. But automatic feed out of thicker work is harder than that of thinner work. Photo 3.3.1(2).6 and Figure 3.3.2(2).3 show an example of full-automatic processing equipment for thick work.

In line with increasing demand for equipment which can cut thicker plates, demand is also rising for machines for cutting materials larger than fixed size materials such as 4 x 8 and 5 x 10 materials. This is because plates are used for structures like concrete frames and in shipbuilding whereas sheets

are used for small items like machine parts. For cutting long plates, the oscillator is attached to the processing machine in some cases because the distance the laser beam can cover is limited. but as the moving section's inertia becomes larger, the processing speed and shape precision may be fairly restricted.

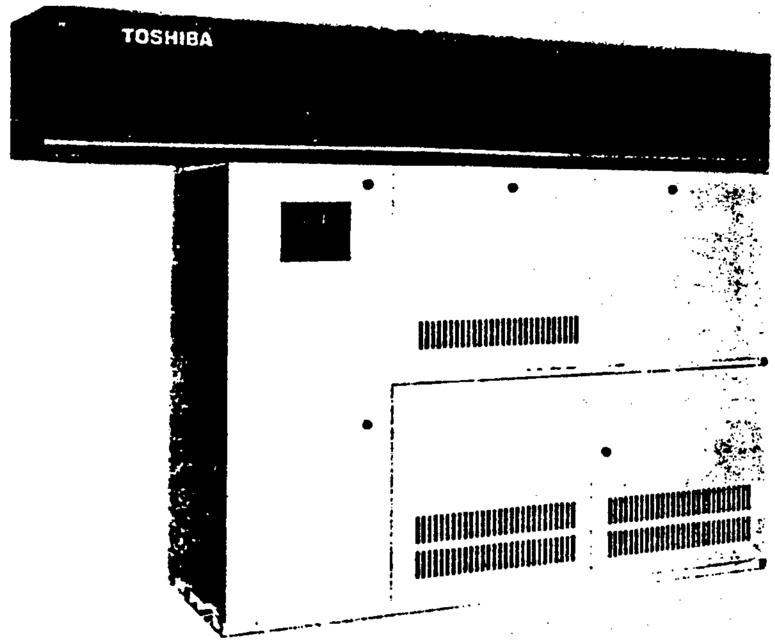

Photo 3.3.2(2).5. External View of 2 kW-Class CO_2 Laser Oscillator (From Toshiba catalog)

The spread of three-dimensional laser processing machines has been remarkable in the past few years and they reportedly account for some 20 percent of the laser processing machine market.[6] These three-dimensional processing machines are mainly used for trimming stamped products in the automotive industry. Such machines have been considered as processing machines for test fabrication, but are now also used on production lines due to an increase in metal mold storage cost stemming from diversifying models and options. There are several types of three-dimensional processing machines, but the mainstay type is a double-housing processing machine equipped with a processing head capable of rotating around two axes. These machines are usually controlled by the teaching playback method, and teaching work is simplified by measuring locus smoothness with free curve interpolation. However, as teaching takes a fairly long time, the important point is

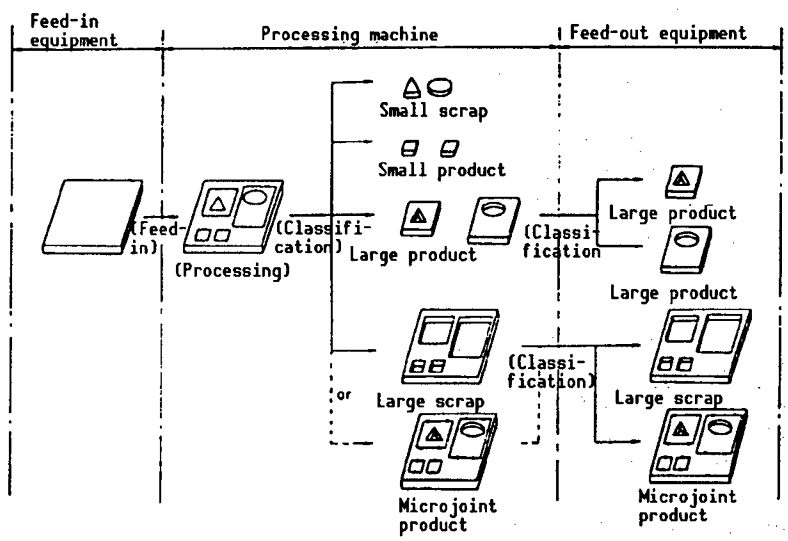

Figure 3.3.2(2).2. Outline of Cut Product Classification (By Matsushita[5])

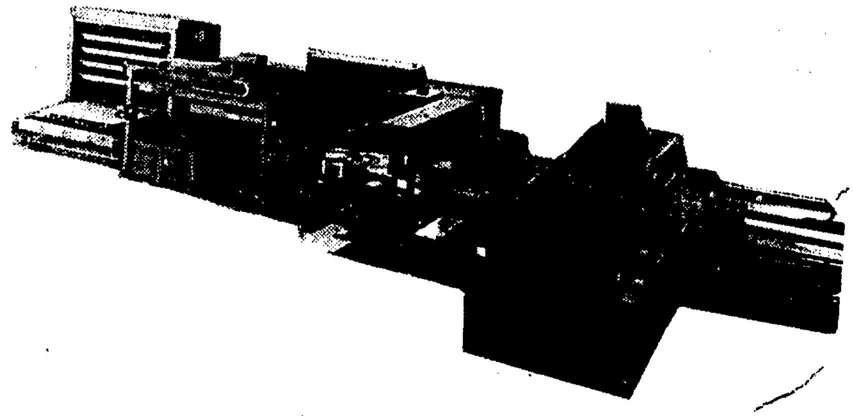

Photo 3.3.2(2).6. External View of Fully-Automatic Plate Processing System (By Matsushita[5])

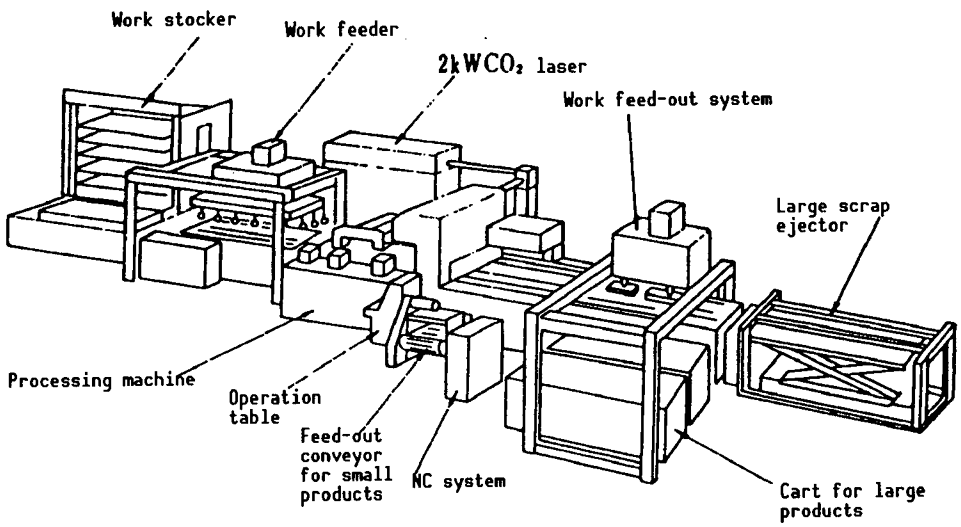

Figure 3.3.2(2).3. Fully-Automatic Plate Processing System (By Matsushita[5])

how simply teaching can be carried out. To facilitate teaching, some machines have touch sensors for teaching and others allow off-line teaching.

A program for three-dimensional processing machines is created through teaching their locus accuracy is slightly lower than that of processing by a numerically-controlled (NC) program. Because the focusing position and laser irradiation angle are not precise, cutting quality is generally inferior to that of two-dimensional processing. But improvement has been made by using highly responsive height sensors.

Laser cutting of highly reflective materials like aluminum and copper has been difficult, but now high-quality cutting of such materials up to about 3 mm thick is possible. The need for laser cutting of aluminum is particularly high and there are many reports on laser aluminum cutting. Oxygen is used as assist gas and oxidizing reaction is used in steel cutting, quality cutting is not

available with oxygen in the case of aluminum. Reports say nitrogen and air work well as assist gas. However, when these highly reflective materials are cut, reflection from work may damage the laser oscillator and optical parts of the transmission optical system. The idea of detecting reflected light and controlling power has been proposed as a measure to prevent this damage, but full protection has apparently yet to be achieved.

(ii) Welding

The share of CO_2 laser welding in the entire CO_2 laser process has shown little growth in the past few years, but the size of their market is steadily expanding as evidenced by the expansion of the total processing machine market. CO_2 laser welding has long been used in manufacturing transmission parts, fuel tanks, and wheels in the automobile industry and is expected to spread further. It is also increasingly used in the steel industry for welding coils.

Laser welding can achieve welding beads comparable to those of electron beams, but building of a welding system requires considering appropriate welding forms from the design stage. In welding sheets, good welding cannot be done unless the gap of the welding section and shift are 0.2 mm or less. Thus, lap welding is the best welding form and butt welding and T-joint welding require the management of the gap and shift.[7]

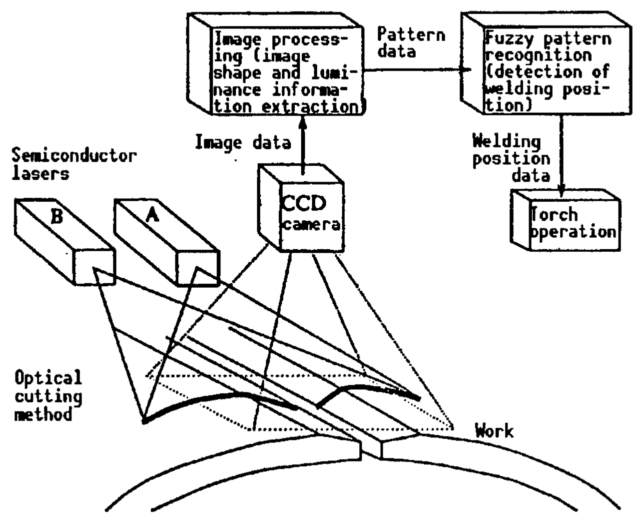

Figure 3.3.2(2).4. Outline of Laser Welding Bevel Sensor (By Sameda, et al.[8])

Accurate bevel processing is necessary to prevent a shift, but actually precision required by laser welding is not satisfied in many cases, necessitating welding line bevel profiling. This profiling operation requires higher precision than conventional welding and there are bevel sensors that have precision good enough for that.[8] Figure 3.3.2(2).4 shows an outline of a bevel sensor. There has been a method under which a slit beam of a semiconductor laser is irradiated to the bevel and its image is processed. The sensor allows welding position detection in 60 msec with precision of ±0.1 mm, using the fuzzy principle in inferring the real welding position, distinguishing it from various noises like surface scratches, in pattern recognition after image processing.

Laser welding of aluminum is difficult because its absorption of CO_2 laser is low, but laser welding of aluminum alloys is now possible by increasing the laser's power density.[9,10] Figure 3.3.2(2).5 shows the suitable range of power density. When He is used as shield gas for welding A2219 and A5052, beads become unstable, but the use of Ar can provide stable beads.

(iii) Surface Reforming

Lasers are very seldom used for surface reforming, except transformation quenching. A laser beam for surface reforming should ideally have a uniform power density distribution over a range as wide as possible. Thus, beam shaping technology using a special condensing optical system is necessary. Figure 3.3.2(2).6 shows such well-known beam shaping methods.[11] A high-output laser is needed in order to process a wide area using these methods and research is under way to use 5~10 kW lasers.

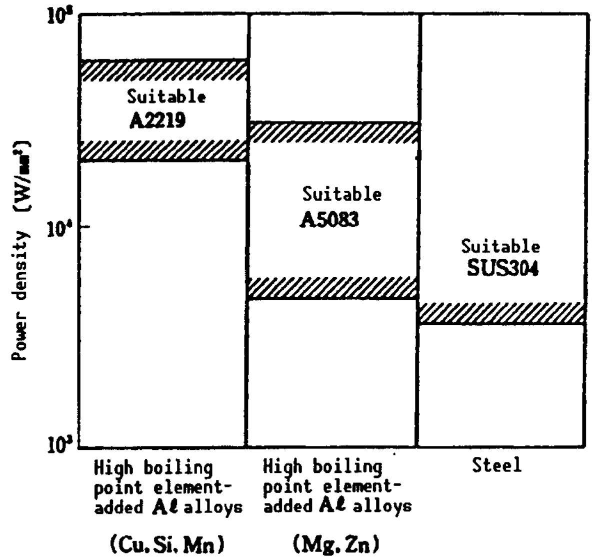

Figure 3.3.2(2).5. Application Range of Al Alloy Laser Welding Seen From Power Density (By Honda, et al.[9,10])

Besides transformation quenching, there are such surface reforming methods as the use of alloys and cladding and active research has long been carried out. As a special example, there is a report on making zeolite-base mortar into ceramics.[12] Zeolite-base mortar ceramics take on color upon melting by laser, and designs can be drawn on the material surface by local heating with an NC laser. At the same time, this is said to be effective in improving surface hardness and reducing water absorptivity.

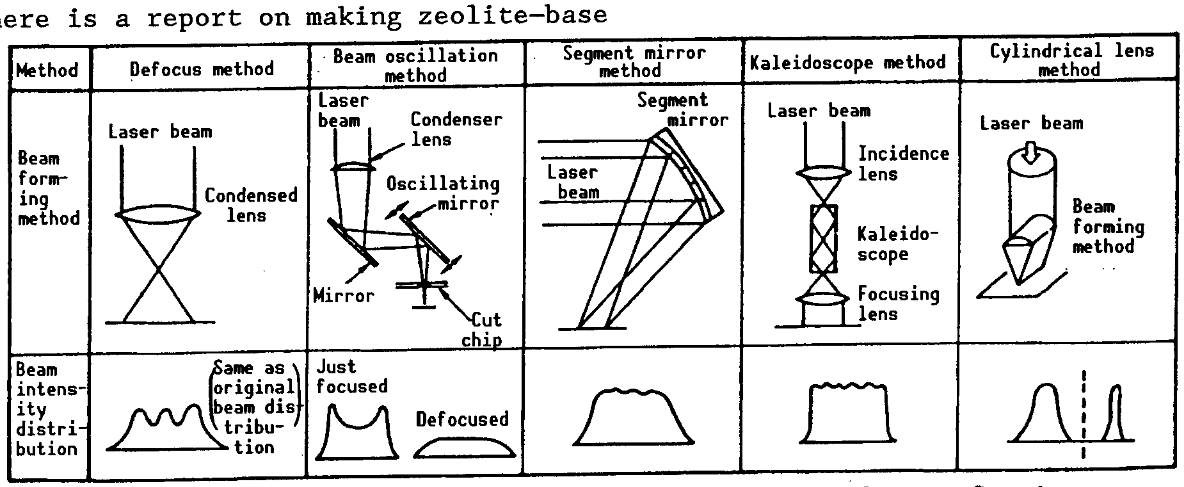

Figure 3.3.2(2).6. Beam Shaping Methods for Surface Reforming (By Morikawa, et al.[11])

A wire-gas coaxial laser crossing method has been reported as a new laser flame spraying method.[13] The use of a special nozzle whose wire and gas feeding is done coaxially enables bombarding the material with sprayed particles at high speed. Low-temperature flame spraying is also possible because the laser beam does not directly hit the material.

(iv) Other Processing

Other processing includes laser glazing, evaporation processing, laser forming, and composite processing. As for the evaporation process, research is under way on alumina and other oxide materials. The use of lasers can deposit film faster than the conventional ion plating method. As the evaporation process is done within a chamber, continuous film deposition is difficult due to damage on the laser transmission window. But there is a report that long-time film deposition was made possible by a mechanism preventing sticking of evaporated particles to the window.[14]

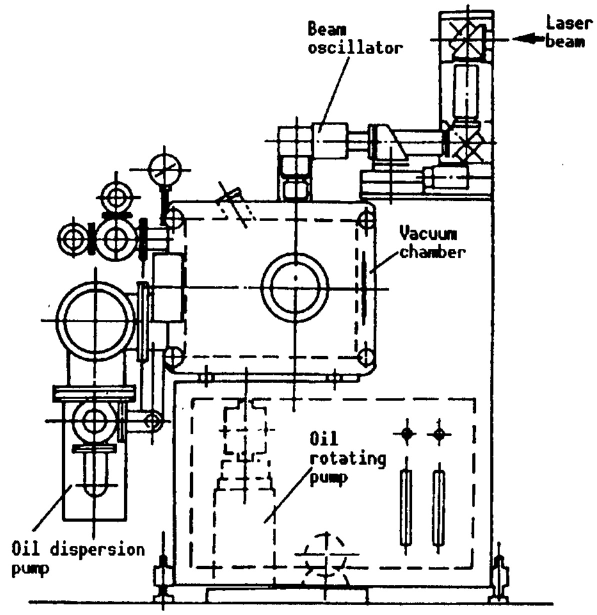

Figure 3.3.2(2).7. Example of Glazing, Evaporation Experimental System (By Morikawa, et al.[11])

Figure 3.3.2(2).7 and Photos. 3.3.2-(2).7 and 3.3.2(2).8 show examples of experimental equipment for glazing and evaporation.[11] It is difficult to put laser forming to practical use because of difficulties involved in controlling the amount of materials removed in the depth direction, but a laser milling machine was introduced at the EMO Show n 1989. It is used for making molds for plastic and rubber products, satisfying the need for shorter delivery time.

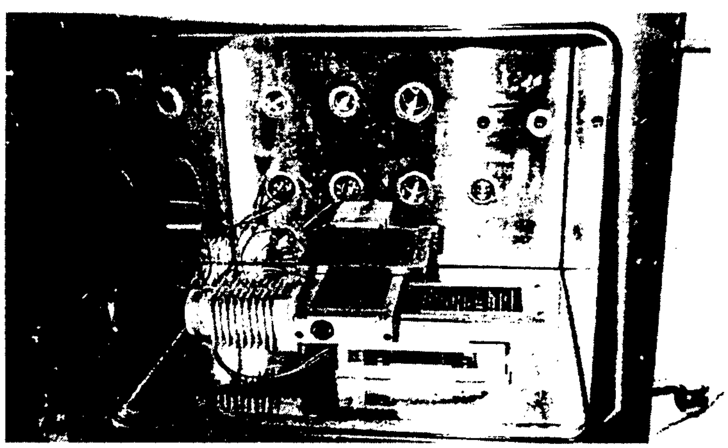

Photo 3.3.2(2).7. Glazing, Evaporation Experiment Chamber (By Morikawa, et al.[11])

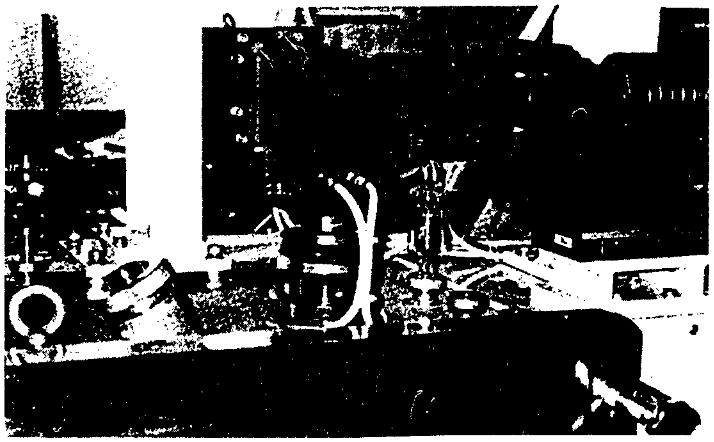

Photo 3.3.2(2).8. Beam Oscillator for Glazing, Evaporation Experiments (By Morikawa, et al.[11])

Laser composite processing includes composite welding of TIG and MIG, composite flame spraying with plasma and laser assisting of cutting. It is reported that ERW-laser composite welding technology has been established in addition to these.[15] The technology is applied to welding steel pipes. ERW's input heat quantity is reduced by combining multiple reflection laser beam condensing at the narrow bevel section and ERW. Super solubility at the plate corner section can be curbed, preventing cooling and enabling high-speed welding that produces a tough welded section. (Yamaguchi)

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Medical Applications for Lasers

926C10150 Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91
pp 459-462

[Text] **3.3.4 Medical Applications**

(1) Medical Laser Systems

(b) Future Technology Trends

Medical applications of lasers can be broadly broken down as: incision and resection, coagulation, optical stimulation, and optical chemical reaction. Technology trends of lasers suitable for these applications are discussed below.

(i) Incision and Resection

Incision and resection are treated as the same function. The Er-YAG laser, which is better absorbed by water than the CO_2 laser, has been developed for this function. This laser has a wavelength of 2.94 μm and is absorbed by water most in the intermediate infrared, near infrared, visible, and ultraviolet wavelength ranges. Its absorptivity is about 10 times that of the CO_2 laser (10.6 μm). The Er-YAG laser is thus able to do better incision and resection work than the CO_2 laser in sections with high water content.

Excimer and other ultraviolet lasers are also gradually being used. These laser beams can cut living tissues sharply at a relatively low temperature. However, the use of ultraviolet rays could cause cancer and it is necessary to clearly set safe irradiation conditions.

(ii) Coagulation

The laser was first applied medically as a retina coagulating system. Coagulation is a treatment as effective as incision or resection. Such treatment includes thermal coagulation of blood and blood vessels and evaporation of water content of the affected tissues to blow them away. Compared with incision and resection, they are softer approaches and have the following features:

a. Coagulating hemostasis
b. Curbing abnormal growth of blood vessels (birthmark removal)
c. Necrosis of cancer
d. Low-energy blood vessel inosculation

The Ar laser is often used to treat cerebral hemorrhage in eyes, detached retinas, and abnormal blood vessel growth, and the Nd-YAG laser is used along with an endoscope, for examinations inside the human body.

(iii) Optical Stimulation

Optical stimulation is treatment using lasers with lower energy than that for incision, resection, and coagulation. The human body has about 300 spots sensitive to stimulation and stimulating these points heals muscle aches, stiff shoulders, and headaches. Laser beam stimulation treatment uses a laser beam to stimulate these spots. Small output is sufficient for this application, but the beam must penetrate into the body. This treatment is old and its effects were found by Dr. Mester of Hungary, who used the He-Ne laser with output of around 2 mW. As no high output is required, the He-Ne laser was most widely used for treatment, but the Nd-YAG, He-Cd, and Ar lasers were also used. The recent advance of semiconductor lasers led to the development of systems using these lasers, making it an active growth field.

(iv) Optochemical Reaction

This is intended for treatment of cancer. A photosensitive substance that can be selectively put into the cancerous tissues and stay there for a long time is brought into the human body and a laser beam whose wavelength is especially well absorbed by that substance is irradiated to destroy the cancerous tissues.

Pigment lasers induced by the argon laser have been used for this purpose, but those induced by the excimer laser are now being developed. A pigment laser is characterized by the ability to change the oscillation wavelength continuously and the laser wavelength is set to that best absorbed by the photosensitive substance.

First-generation laser medicine is defined as raising the temperature of a living tissue to thermally cut, remove or coagulate it. Second-generation laser medicine uses low-output lasers for photochemical action.

Laser oscillator development is oriented toward shorter wavelengths and efforts are being made to develop new technologies like ultraviolet lasers, X-ray lasers and free electron lasers (FEL) with a wide variable wavelength range and high optical output. If realized, they will open the way for new medical applications. Active research on medical applications of ultraviolet lasers is already under way and there are signs that such lasers will find their way into not only clinical medicine, such as gene injection through microscopic processing of cells, but also basic medicine and wide areas of cell bioengineering.

There are currently about 30 FEL systems in the world and research is continuing to use them for clinical applications. Regrettably, Japan lags behind others in this research.

FELs with variable wavelengths and output scalability are best suited to basic research on mutual action of coherent light and a living body.

Interesting moves are efforts to shorten laser wavelengths and make wavelengths variable. Shorter-wavelength lasers mean X-ray lasers which, if realized, will revolutionize radiation diagnostics. Actually, FEL must be inserted into and operated within a storage ring capable of a large current and high-acceleration voltage and the largest problem involved is the deterioration of the quality of the electron beam after passing through FEL. It is significant that an X-ray laser fills a region from far infrared to submillimeter waves lacking in variable-wavelength FEL laser. In the wavelength range, a linear accelerator is good enough as the electron beam source and the possibility of realization is large. As there is no light source that fills this range, little study has been done on optical properties of all substances. A theoretical model has been reported hinting at the possibility of far infrared coherent light affecting life activities by causing a peculiar vibration mode to proteins that make up cells. It will thus become possible to study coherent mutual action of substances constituting a living body and light. A FEL at the University of California at Santa Barbara is already operated for joint use in properties research and study on biogenetic substances.

Others which are expected to be used as medical lasers in the near future are semiconductor lasers and semiconductor laser-induced YAG lasers. Semiconductor lasers are very compact and some recent models have optical output in the order of watts They are promising as lasers for optical stimulation treatment. As each element of semiconductor lasers is small, many can be bundled to obtain high optical output. Moreover, efforts are being made to develop those with an oscillation wavelength close to that of the Nd-YAG laser. When realized, it will be even more compact than existing models and prove very suitable for medical applications.

Trends To Increase Efficiency, Reliability of Solar Batteries

926C1015P Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 471-479

[Text] **3.3.5 Energy Generation**

(1) Solar Batteries

Against the background of the aggravation of global environmental problems and the unstable oil situation stemming from the Gulf situation, regenerative energy, particularly solar power generation, is attracting more attention. Under the Sunshine Project, the New Energy Development Organization (NEDO) is promoting the development of optical power generation technology with the aim of achieving full-scale introduction of optical generation at the beginning of the 21st century. To this end, it is necessary to reduce the manufacturing costs of solar batteries to ¥100~200/W. Currently, the cost is around ¥700/W and further efforts are needed to lower it and increase conversion efficiency.

NEDO is conducting research on commercializing new solar batteries, centered on polycrystalline silicon batteries, and amorphous solar batteries under a four-year program which started in FY89. In the current fiscal year, it also launched a project to develop superhigh-efficiency solar battery technology, designed to nearly double conversion efficiency. Materials subject to this project are crystalline silicon, amorphous silicon, compound semiconductors, and compound semiconductor thin films. Recent technology development trends of these various solar batteries and market trends, centering on production volume, are explained below.

(a) Technology Trends

(i) Single-Crystal Si

Research and development efforts on single crystal Si solar batteries have long been made and many such batteries are actually used. Conversion efficiency is increased mainly by reducing recoupling of optically generated carriers and boosting carriers generated by effectively confining light. For a reduction in the recoupling speed, efforts are being made to develop: 1) technology to passivate defects by implanting H ions into the substrate

surface or depositing oxide film; 2) the back surface field (BSF) structure; and 3) technology to lower recoupling near the electrode through a decrease in and concentrated doping of the area contacting the electrode. As for effective confinement of light, efforts center on developing 1) technology to make film to prevent reflection and 2) technology to make grooves on the surface (back). Taking these issues into account, several new device structures have been proposed. Recent progress of these technologies to boost efficiency is discussed below.

New South Wales University of Australia developed the passivated emitter, rear locally-diffused solar cell (PERL) structure as shown in Figure 3.3.5(1).1 and achieved conversion efficiency of 24.2 percent for a 4 cm^2 device.[1] It is an improved version of the passivated emitter and rear cell (PERC) structure which has unevenness of an inverted-pyramid shape on the cell surface and achieved conversion efficiency of 23.2 percent last year. A highly-doped layer (P^+ layer) placed only in the point electrode section of the back curbs recoupling around the electrode. This PERL cell achieves high efficiency of 26.7 percent at 10-fold condensing (10 sun) and with a prismatic lens (which prevents the blocking of condensed light by the surface electrode).

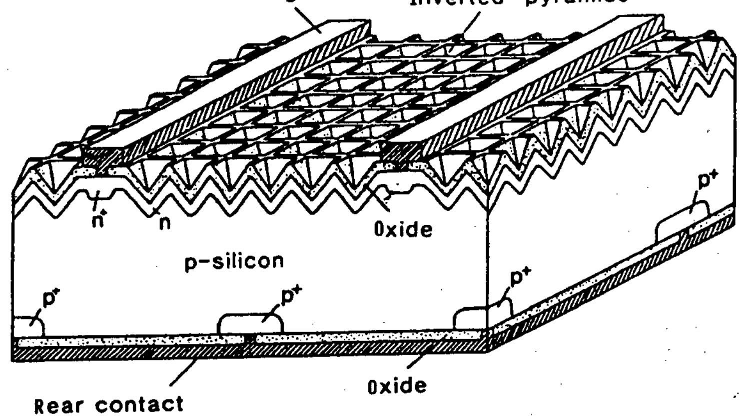

Figure 3.3.5(1).1. PERL Cell

Stanford University of the United States developed a point contact solar battery and achieved conversion efficiency of 28.5 percent (100 sun). This structure later proved to be prone to deterioration due to light, but the university showed that stability can be improved by applying phosphor in between Si and the passivation film from the surface and forming a floating N^+ layer.[2]

In Japan, Hitachi, Ltd., proposed a corrugated structure having V grooves on both sides, as shown in Figure 3.3.5(1)-.2, and Hoxan Corp. developed an element in which fine printed electrodes are used in the conventional passivated emitter solar cell (PESC) structure.

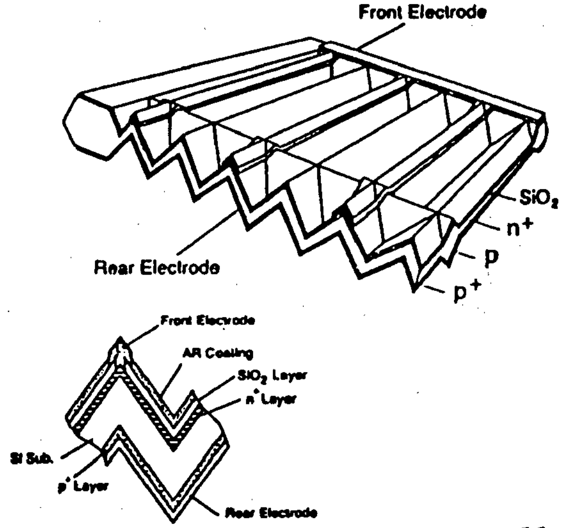

Figure 3.3.5(1).2. Corrugated Cell

Meanwhile, conversion efficiency of solar battery modules available on the market has steadily been improving and Sharp Corp attained efficiency of 17.1 percent.

(ii) Polycrystalline Si

NEDO is conducting a wide range of R&D from manufacturing technology for Si materials to substrate manufacturing technology and technology to make high-efficiency cells.

Regarding materials, technology continues to develop to decarbonize and refine silicon made by carbon thermal reduction of refined silica in order to manufacture solar battery-grade Si (NEDO direct reduction method).

In the substrate manufacturing field, efforts are under way to develop an electromagnetic casting method using equipment shown in Figure 3.3.5(1).3 (Osaka Titanium Co.).[4] This method needs no crucible because molten Si is maintained by electromagnetic force. It is attracting attention as it can prevent mixing of impurities from a crucible and mold separating material. Currently, 117-mm^2 ingots are manufactured. As for thin-slicing technology, which is important for substrate cost reduction, thinness of up to 200 μm is now possible. The problem to be solved next is a reduction of the margin for cutting. As technology to make sheet substrate that needs no slicing, the spin-cast and cast-ribbon methods are under development (Hoxan).

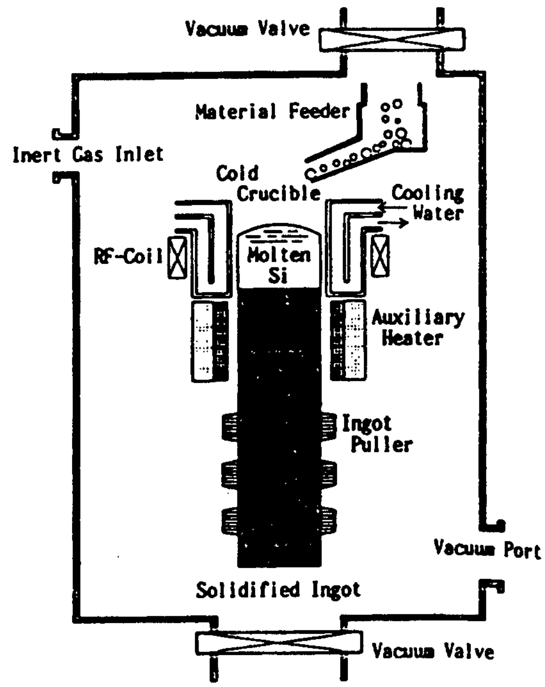

Figure 3.3.5(1).3. Electrode Casting Equipment

Improvement of cell efficiency is being done using basically similar approaches to those taken for single crystal Si cells. Major announcements made in 1990 on conversion efficiency improvement are as follows:

Efficiency of 15.6 percent for a large-scale solar battery measuring 15 cm^2 and 300 μm thick[5] (Kyocera Corp.)

Efficiency of 15.5 percent for 10 cm^2 cell having V grooves made by a dicing machine[6] (Sharp Corp.)

Efficiency of 16.7 percent for 10 cm^2 cell with laser-processed grooves[7] (New South Wales University)

(iii) Amorphous Silicon

Active R&D activities are being carried out at many organizations regarding amorphous silicon (a-Si) solar batteries on the ground that cost reduction is considered easy. The development of technology for higher reliability is also important for a-Si solar batteries along with the development of technology for higher efficiency in order to prevent the drop in efficiency under irradiated light. For higher efficiency and reliability of a-Si solar batteries, the most important issue is the development of high-quality materials. This is a point that is basically different from crystalline Si batteries whose emphasis is placed on the device structure. Recent development trends of technologies for higher efficiency and higher reliability are discussed below.

(a) Technology for Higher Efficiency

Measures being taken for higher efficiency are improvement of doping layer (P layer) quality, improvement of transparent electrode performance, improvement of the interface between the transparent electrode and the P layer, development of new film deposition technology, use of tandem cells and improvement of alloy film quality to that end, and use of different materials in tandem.

As for the P layer, Fuji Electric Co. used the pulse plasma method using BF_3 as the doping gas[8] and the Konagai Lab of Tokyo Institute of Technology used the delta doping method[9] to achieve conversion efficiency of 12.0 percent each for a small cell. Many attempts are being made regarding new film deposition methods designed to replace the usual plasma chemical vapor deposition (CVD) method. They include VHF (Oda Lab of Tokyo Institute of Technology), ECR (Hiroshima University), reactive ICB (Osaka University), and microwaves (Kyoto University).

Tandem solar batteries include the a-Si/a-Si two-layer structure and two- or three-layer structures using a-SiC, a-SiGe and other alloy films. The former structure achieved efficiency of 11.6 percent (Fuji Electric) and the latter 13.7 percent (ECD). As alloy film quality improvement is limited, active efforts are now being made to achieve high efficiency with the use of different materials in tandem. Efficiency of 16.8 percent is achieved with a cell using crystalline Si (Osaka University) and 15.6 percent with a cell using $CuInSe_2$ (compound thin film) (Siemens Solar).

Table 3.3.5(1).1 shows efficiency of major single-type, high-efficiency a-Si solar batteries. The highest efficiency for a small a-Si single cell is a uniform 12 percent for seven research institutions, six of which are Japanese. As for large cells, efficiency is 10.6 percent for a 100 cm^2 cell (single type, Sanyo Electric Co.), 10 percent for a 1,200 cm^2 cell (a-Si/a-Si type, Fuji Electric), and 10.5 percent for a 3,905 cm^2 cell (a-Si/$CuInSe_2$ type, Siemens Solar). The efficiency gap between small and large cells is thus narrowing gradually.

Table 3.3.5(1).1. High-Efficiency a-Si Solar Batteries (Single-type small Cells)

Voc-(V)	Jsc (mA-/cm)	FF	EFF (%)	Area (cm^2)	Announced by	Remarks
.967	17.7	.703	12.0	0.033	Osaka University	p-μc(ECR)
.857	18.7	.749	12.0	1.0	Mitsui Toatsu Chemical	multi-P
.895	18.4	.728	12.0	1.0	Hitachi	multi-P
.89	18.3	.74	12.0	1.0	Sumitomo Electric	
.891	19.1	.70	12.0	1.0	Solarex	
.927	18.4	.705	12.0	1.0	Fuji Electric	BF_3-pulse
.88	18.4	.742	12.0	0.09	Tokyo Institute of Technology	δ dope P

(b) Technology for Higher Reliability

In order to improve reliability, material approaches are being made to control hydrogen within a-Si film. Shimizu, et al. (Tokyo Institute of Technology) propose a chemical annealing method under which atom hydrogen is introduced during the a-Si film growth process in order to expedite Si grids.[10] A method proposed by Mitsui Toatsu Chemicals, Inc. calling for repeating plasma CVD and hydrogen plasma processing also aims at a similar effect.[11] These and a reduction of the hydrogen amount within the film through high-temperature deposition of a-Si film (Sanyo Electric) are still in a rudimentary stage and the future problem is their application to devices.

The tandem structure is also promising as technology for higher reliability. Fuji Electric attained efficiency of 10 percent (initial deterioration rate 12.3 percent) for an a-Si/a-Si two-layer tandem cell (1 cm^2) after continuous light irradiation of 1,000 hours (100 mW/cm^2).

(iv) Compound Semiconductors

Because of their high efficiency and high prices, solar batteries using GaAs, InP, and other III-V family compounds have been developed chiefly for use in space applications. Future development directions will be: the highest possible efficiency and reducing cost for ground applications. The major issue of technology for higher efficiency is the use of the tandem approach that capitalizes on a wider selection of materials than Si, while technology for lower cost centers on manufacturing a solar cell (thin-film type) on Si and other cheap substrates. The current development status of single-junction and tandem cells is explained below.

(a) Single-Junction Type

Among GaAs-substrate cells, a cell using GaInP (conventionally AlGaAs) for the window layer has achieved the highest efficiency ever of 25.7 percent (SERI).[12] As for condenser types, Spire of the United States reported efficiency of 28.7 percent under a 200-fold concentrated light.[13] Meanwhile, efficiency of InP-substrate cells has also improved and Spire has achieved 19.1 percent under AMO light and NTT 22 percent under AM1.5 light. In 1990, InP cells were placed on board the MUSES-A scientific satellite.

Among thin-film cells, a GaAs cell with an Si substrate has achieved efficiency of 18.3 percent (AMO) and 19.9 percent (AM1.5, 210-fold concentration), and a GaAs cell with a Ge substrate 20.8 percent, coming closer to matching the performance of a GaAs-substrate cell. There is a CREFT cell[14] as shown in Figure 3.3.5(1).4 as a different approach to the manufacture of thin-film cells. This structure attracted attention by achieving efficiency of 22.4 percent (AM1.5) and 23.5 percent (AMO, 100-fold concentration).

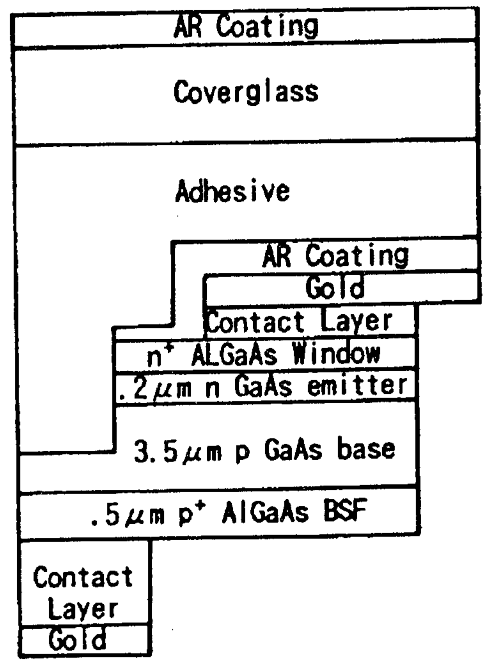

Figure 3.3.5(1).4. CREFT Cell

(b) Tandem Type

Tandem-type cells using III-V-family compounds are expected to have the highest efficiency among solar batteries and various batteries are under consideration in terms of both materials and structures. Classified by structure, there are the monolithic type having multiple junctions in series on a single substrate and the mechanical stack type in which cells made on separate substrates are mechanically pasted together. Hybrids of both are also being made. Table 3.3.5(1).2 shows major structures announced so far. The GaAs/GaSb four-terminal mechanical stack cell manufactured by Boeing Co. has very high efficiency of 35.8 percent at AM1.5, 100-fold concentration.[15]

(v) Compound Semiconductor Thin Film

As II(I-III)-VI-family compounds feature a variable optical gap and small quality deterioration when made into thin film, researchers are studying them as materials that facilitate cost reduction and cell size increase. Materials subject to such research are CdTe-base materials and $CuInSe_2$ and other calchopyrite-base materials.

(A) CdTe

As CdTe's 1.5 eV optical gap and large absorption coefficient are considered ideal for the optoelectric conversion layer of a single-junction solar battery, researchers are making efforts to develop a CdS/CdTe solar battery

Table 3.3.5(1).2. Conversion Efficiency of Compound (III-V) Tandem Solar Batteries

Structure	Conversion efficiency	Measurement conditions	Announced by
GaAs/GaSb mechanical	35.8	AM 1.5 100 Sun	Boeing, Sun Deer National Institute
GaAs/Si mechanical stack	31	AM 1.5 350 Sun	Varian, Sun Deer National Institute
GaInP/GaAs monolithic	27.3	AM 1.5 1 Sun	SERI
GaAlAs/GaAs monolithic	27.6	AM 1.5 1 Sun	Varian
InP/GaInAs monolithic	24.1	AM 1.5 1 Sun	SERI, Varian
Mechanical stack of GaAlAs/GaAs and InGaAs	24.9	AM 0 1 Sun	Varian

with an N-type CdS window layer. Relatively low-cost approaches are being made to make CdTe film, such as the electrochemical method, spray method, and printing and sintering method, producing good results.

The highest conversion efficiency achieved so far is 13.1 percent for a cell Queensland University made by electrochemically precipitating CdS and CdTe one after another on glass/ITO, although the cell size is small at only 0.02 cm^2.[16] Photon energy attained efficiency of 12.3 percent by using either the evaporation method or spray method, and Matsushita Battery Industrial Co. 11.3 percent with the printing and sintering method. The use of wide-gap materials, such as SnO_2, ITO, ZnO, and CdZnS, as window layer materials is also under study in order to increase efficiency further.

Improved efficiency is also coming about for large cells. BP Solar achieved 9.5 percent for a 706 cm^2 cell with the electrochemical method and Matsushita Battery 8.1 percent for a 1,200 cm^2 cell with the drawing and printing method.[17]

(B) $CuInSe_2$ (Calchopyrite)

Calchopyrite $CuInSe_2$ has the largest absorption efficiency among solar battery materials and its optical gap is relatively small at 1.0 eV. Therefore, development efforts assume its use in the bottom layer of tandem-type solar batteries. Possible top cell materials are a-Si whose optical gap is 1.7~1.8

eV and wide-gap calchopyrite materials like $CuGaSe_2$. For $CuInSe_2$ film making, the selenization, three-source simultaneous evaporation, spraying and printing methods are being studied, and conversion efficiency of more than 10 percent is attained by the selenization and three-source simultaneous evaporation methods. Selenization uses H_2Se gas or Se vapor as the selenium supply source and CIS thin film is made by annealing Cu/In laminated film or Cu-In alloy, while the three-source simultaneous evaporation makes a ternary compound by simultaneously evaporating Cu, In, and Se onto a heated substrate.

Siemens Solar achieved efficiency of 14.1 percent with a 3.5 cm^2 cell and 9.7 percent for a large 3,905 cm^2 module. When these are made into tandem units using a-Si, efficiency becomes 15.6 percent and 10.5 percent, respectively—the highest figures for a thin film solar battery.[19] The $CuInSe_2$ film manufacturing method is not disclosed, but presumed to be selenization. With selenization, ISET achieved efficiency of 10.9 percent.

In the case of three-source simultaneous evaporation, generally a two-layer $CuInSe_2$ film is made as shown in Figure 3.3.5(1).5. With this structure, Boeing achieved efficiency of 12.9 percent.[19]

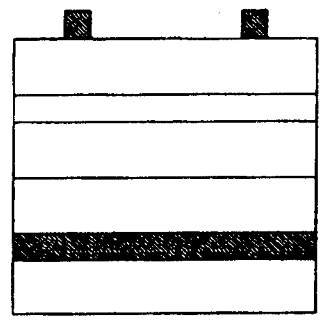

Figure 3.3.5(1).5. Cell Structure Using Two-Layer $CuInSe_2$ Film (Three-source simultaneous evaporation)

The history of full-fledged R&D in this field is still short in Japan, but efficiency at last reached more than 10 percent (10.5 percent, three-source simultaneous evaporation, Fuji Electric).

So far, research has been made only on a very limited number of a wide variety of calchopyrite materials. It is hoped that research will be carried out over a wider range in the future.

(b) Market Trend

Figures 3.3.5(1).6, and 7 shows annual solar battery output (by country and type) compiled by PHOTOVOLTAIC NEWS.[20] World production for 1989 was 42.1 MW, up about 20 percent over the previous year. By type, the growth of crystalline Si was sharp, but output of a-Si dipped. Japan's growth was slow due to a slowdown in demand in the consumer electronics sector (which chiefly uses a-Si), where Japan has been dominant. Nonetheless domestic production increased about 9 percent because crystalline Si for power utilities is rising for export on account of environment problems. This trend is expected to continue.

The use as outdoor power sources is increasing mainly in Europe and the United States. At present, solar batteries are used chiefly as independent power sources in remote areas, but in some places, they are already used together with power grids as in California.

In Japan, the market is in the stage of seeking individual home applications and medium- and large-scale power generation applications in the future, shifting from the stage of use in small consumer items such as electronic calculators. To realize the introduction of full-scale photovoltaic power generation, it is necessary to further improve efficiency of solar batteries and reduce costs as well as to 1) develop peripheral technologies, 2) improve the legal aspect, and 3) develop demand that fills the gap between small consumer items and outdoor power source applications. As for item (1), NEDO is studying cost reduction for peripheral technologies and the development of systems technology for various applications, and solar batteries already have technologically reached a stage where they can be used in combination with the existing power grid. As for item (2), the Electric Enterprises Law was partly revised as of 1 June 1990 for easing regulations. This made it unnecessary to appoint a chief engineer (notice to the safety association) and changed the approval system for work plans to the report system, but the revision is still insufficient because solar batteries cannot be used in connection with the power grid. As for item (3), promising fields are public facilities like street signs, housing-related equipment like ventilation and lighting, and automotive devices like sunroofs.

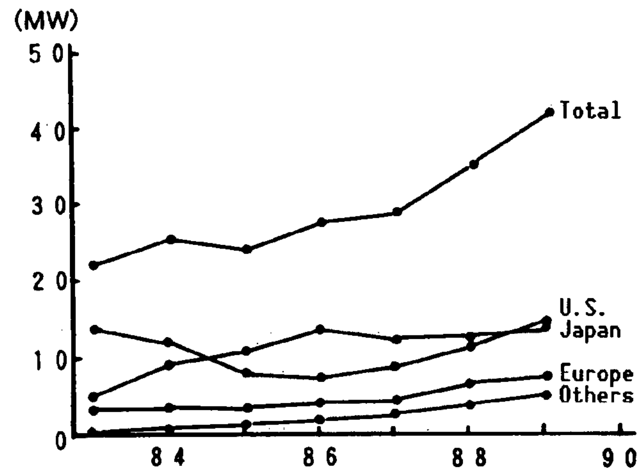

Figure 3.3.5(1).6. Transition of Annual Solar Battery Production (By country)

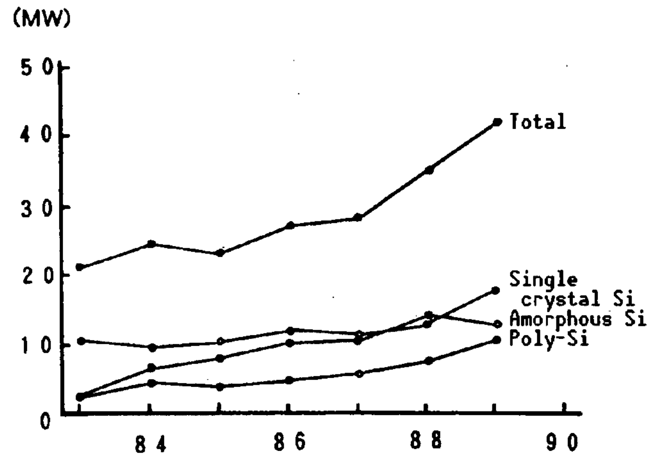

Figure 3.3.5(1).7. Transition of Annual Solar Battery Production (By type)

The world market for optical power generation-related products is expected to reach several trillion yen a year in the future, matching the scale of the semiconductor market. To achieve this figure, cost reduction for entire systems is necessary. But when social costs, such as expenditures for the removal of environmentally harmful substances, are included, optical power generation can fully compete with other generation systems even at the present cost level, a report says.[21] Thus market expansion depends on people's awareness of environmental issues. Financial assistance, including tax incentives for introducing optical power generation and assistance for electrification of developing countries with optical power generation, will naturally be necessary as well. (Ichikawa)

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Developments in Magneto-Optic Materials

926C1015Q Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 499-511

[Text] **4.3 New Materials Development Trend**

4.3.1 Magneto-Optic Materials

(1) Development Trend of Magnetic Field Modulation Overwrite Recording Materials

(a) Magnetic Field Modulation Overwriting Method

The magnetic field modulation recording system reverses the polarity of a magnetic field applied in accordance with information to be recorded while irradiating a continuous laser beam. As signals are taken care of by the magnetic head, the recording principle is close to magnetic recording. By magnetic head structure, the method can be classified into the three categories of: 1) a system using a small magnetic coil placed at a fixed position,[1] 2) a system using a floating magnetic head,[2] and 3) a system which forms an LC resonance circuit using an electromagnetic coil.[3]

In the fixed magnetic coil system, the recording film and the electromagnetic coil is separated by 0.1~0.5 mm, necessitating a relatively large electromagnetic coil in order to apply a magnetic field strong enough to be a predetermined range. As a result, the coil's inductance increases, making high-speed magnetic field modulation difficult. Therefore, this method has been used to record digital audio signals of up to 1 MHz.[4] Recently, a new magnetic field modulation method was devised, which achieved a high speed by irradiating a pulse beam in synch with the magnetic field reversal.[5] Figure 4.3.1.1 shows its timing chart. Taking into account a delay in thermal response, a pulse beam is irradiated tens of nanoseconds before the magnetic field reaches its maximum strength. Figure 4.3.1.2 shows the modulation transfer function (MTF) calculated from recorded solitary waveforms in the case of a continuous beam and in the case of a pulse beam.[6] Compared with the pit shapes recorded by a continuous beam, the pit edges are sharper when recorded by a pulse beam as high-speed modulation eliminates unsaturated magnetic domains.

As the coil-recording film distance is short at around 10~15 μm in the floating magnetic head system,[2] though it depends on the head shape, a relatively high magnetic field can be modulated by a high frequency. Figure 4.3.1.3 shows an example of the floating magnetic head structure. Using a single-polarization coil, the magnetic field reversal time of 15 ns (±200 Oe) and the generated magnetic field intensity of more than 300 Oe are achieved in a magnetic field-applied domain of 0.2 x 0.2 mm to 0.1 x 0.1 mm.[7] As this system uses contact start/stop, there is concern about the disk's anti-abrasion characteristics and the head's durability in a dusty environment. But there are reports on improvement, such as the addition of a resin protective coating about 10 μm thick[8] and achieving coating film strength similar to that of a magnetic disk by coating a-Fe_2O_3 impregnated with a lubricant.[9]

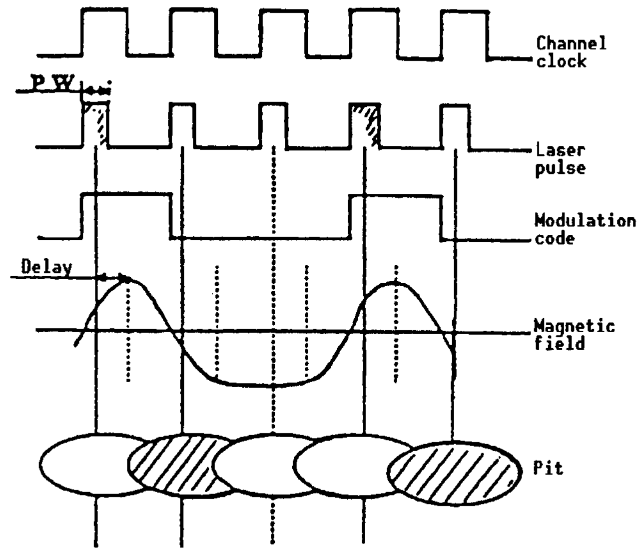

Figure 4.3.1.1. Timing Chart for Pulse-Synchronized Magnetic Field Modulation (By Watanabe, et al.[5])

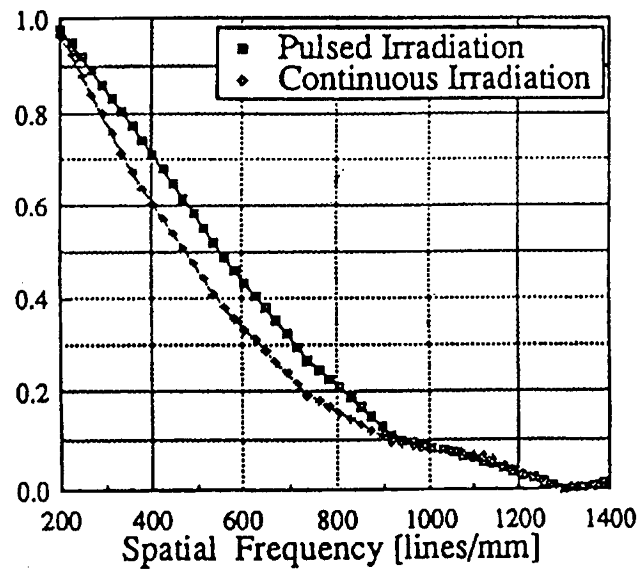

Figure 4.3.1.2. MTF Characteristics of Pulse-Synchronized Magnetic Field Modulation (By Watanabe, et al.[6])

The resonance circuit method[3] carries out overwriting by irradiating recording pulses timed to the positive and negative of the magnetic field generated by the resonance circuit (see Figure 4.3.1.4). Its advantage is that a large magnetic field can be obtained, but pits recorded become large as against the magnetic field frequency because of low resolving power of thermal diffusion on an analysis of the results, a 5.25-inch magnetic field modulation magneto-optic disk drive was test-manufactured.[18] The control section and power source of the drive are installed externally to make it a full-height size. It has an average access time of 60 ms and transfer speed of 2.2 MB/s. By shrinking the shortest pit length to 0.6 μm and narrowing the tracks (1.4 μm pitch), recording density of 600 MB is achieved for one side of the disk.

(2) Trend of Light Modulation Overwriting Recording Materials

(a) Optical Coupling Multilayer Film Light Modulation overwriting Recording Materials

In light modulation overwriting using exchange coupling multilayer film, data recording and erasing are done simultaneously by modulating the light intensity between the two levels of high and low. A two-magnet system[18,19] and one-magnet system[20] are proposed. The two-magnet system requires at least two magnetic layers and the one-magnet system at least four, but their basic principles are the same.

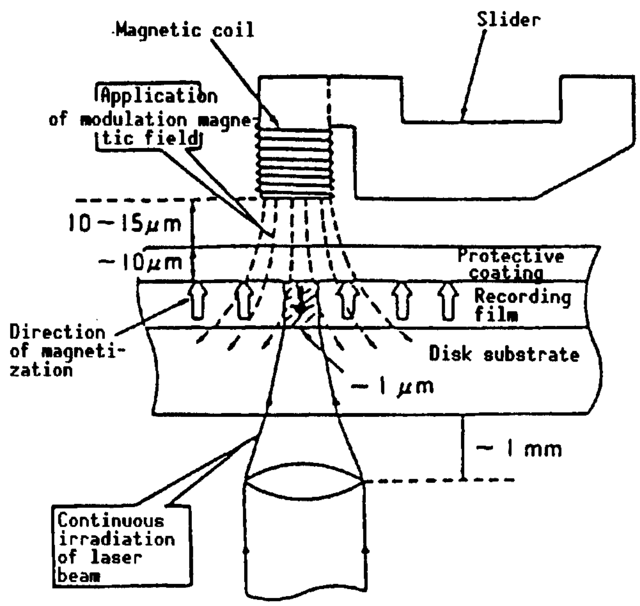

Figure 4.3.1.3. Structure of Floating Magnetic Head (By Nakao, et al.[7])

Figure 4.3.1.7 shows the principle of light modulation overwriting of the two-magnet system. The second magnetic layer (writing layer) needs to be initialized before irradiation by a laser beam. This is done by a magnet for initialization in the two-magnet system and the fourth magnetic layer (initializing layer) in the one-magnet system. When low-level light is irradiated after the initialization, exchange coupling force aligns the transition metal spin of the first magnetic layer (memory layer) with that of the second magnetic layer, erasing the old data to record "0." When high-level light is irradiated, magnetism of the second magnetic layer with a high Curie temperature is reversed by the external recording magnet. In the one-magnet system, magnetism of the fourth magnetic layer does not affect the reversal of the second magnetic layer at

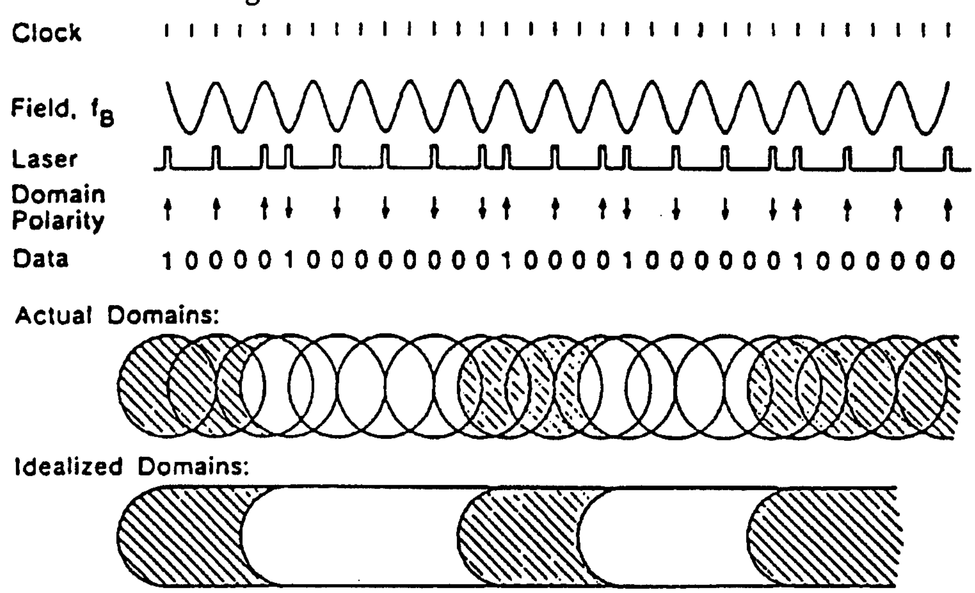

Figure 4.3.1.4. Magnetic Field Modulation Overwriting Using Resonance Coil (By D. Rugar, et al.[3])

all because the Curie temperature of the third magnetic layer (switching layer) is set low. Then the disk is cooled and the first magnetic layer's magnetism appears in alignment with the second magnetic layer's, recording "1." Then the second magnetic layer is initialized by he initializing magnet in the two-magnet system and the fourth magnetic layer via the magnetized third magnetic layer in the one-magnet system.

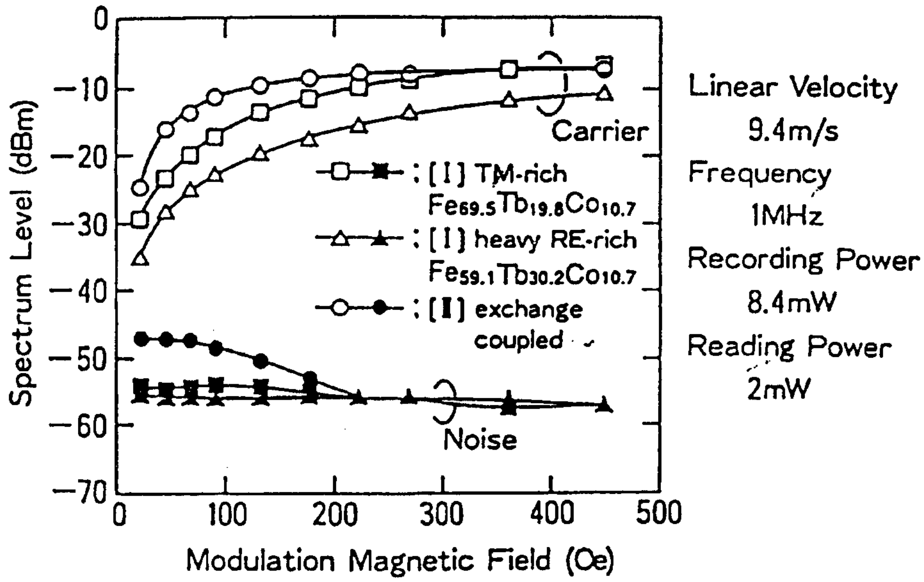

Figure 4.3.1.5. Dependence on External Magnetic Field of Magnetic Field Modulation Media (By F. Tanaka, et al.[15])

Mainly TbFeCo is used for the first magnetic layer. It is a material with high coercive force and suitable for string recorded information. Materials mixing two rare earth metals, such as TbDyFeCo, GdTbFeCo, and GdDyFeCo are used for the second magnetic layer in order to adjust the layer's room temperature coercive force to facilitate initialization. The adjustment of each magnetic layer's Curie temperature is done by changing the amount of Co added. The Curie temperature determines the power margin against overwriting. In the two-magnet system, for example, TbFeCo is used for the first magnetic layer and TbDyFeCo for the second magnetic layer to achieve C/N of 47 dB and low-level light margin of ±20 percent at the mark length of 0.76 μm.[21] Similarly, in the one-magnet system, there are overwrite margins against high-pulse light and pulse width, as shown in Figure 4.3.1.8.[22]

The most important thing in light modulation overwriting is control of interface domain wall energy. In Figure 4.3.1.7, in "1" after the initialization, the spin directions of the first and second magnetic layers become opposite to each other and interface domain wall energy σw is stored in their interface. In this state, status "1" is higher than status "0" by σw in terms of energy and initialization becomes easier when σw is smaller. But if σw becomes too small, erasing by exchange coupling force becomes impossible, making it necessary to control it to an optimum value. To this end, insertion of an anisotropic intermediate film is made between the first and second magnetic layers.[19] As σw gets smaller as the intermediate layer becomes thicker, in accordance with the calculation results[23] shown in Figure 4.3.1.9, it is easy to design σw to an optimum value.

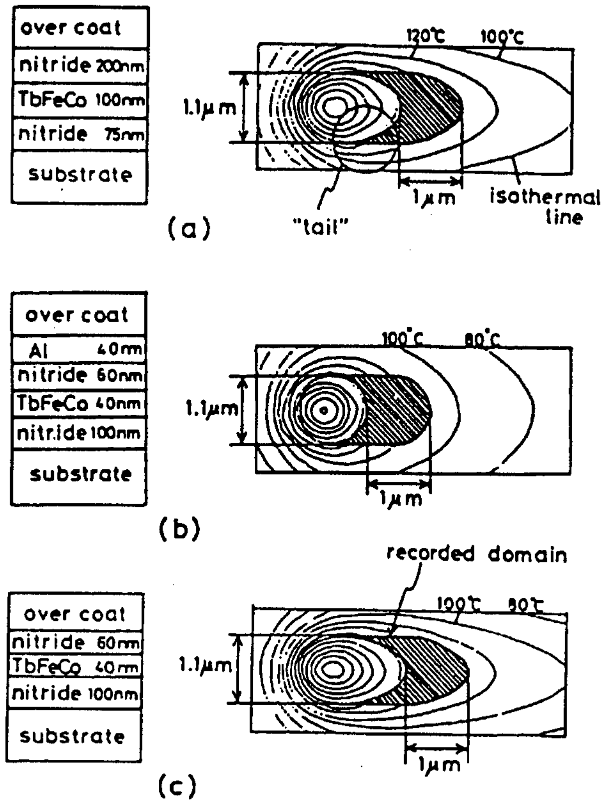

Figure 4.3.1.6. Disk Structures and Recording Domain Shapes (By Miyamoto, et al.[17])

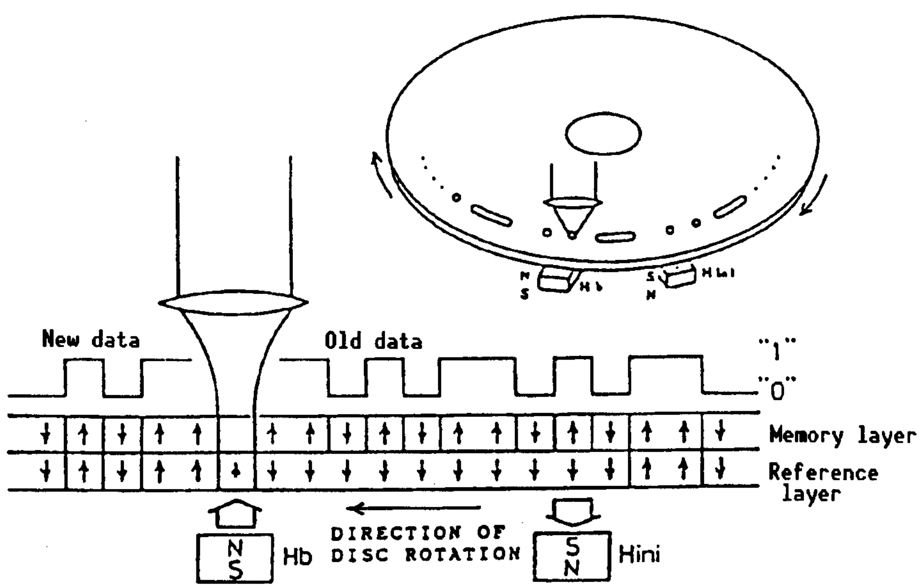

Figure 4.3.1.7. Principle of Light Intensity Modulation Overwriting (By H. Iida, et al.[21])

(b) Recording Materials for Single-Layer Film Light Modulation Overwriting

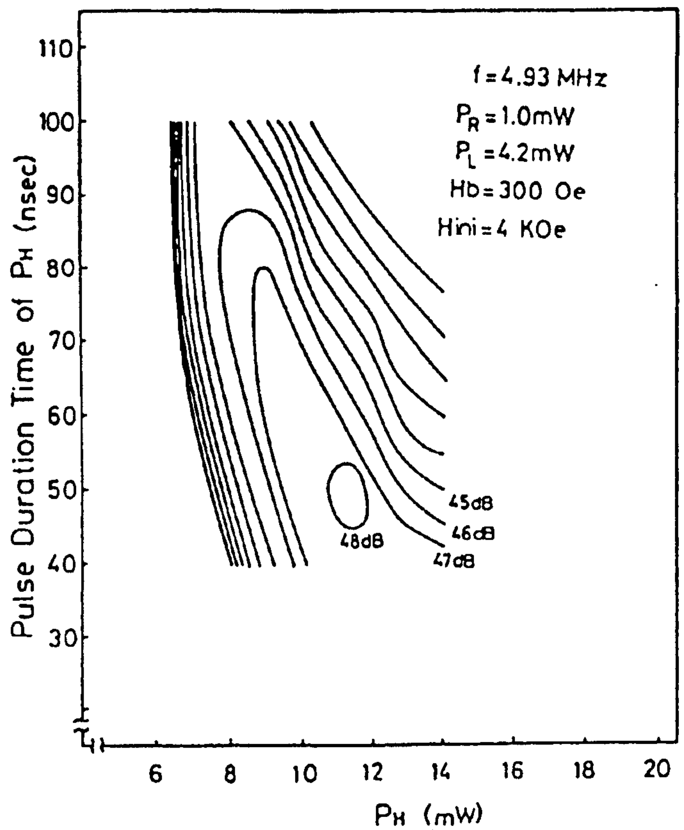

Figure 4.3.1.8. Power Pulse Width Margin of Light Intensity Modulation (By Tsutsumi, et al.[22])

M.H. Kryder, et al., showed that in TbFeCo single-layer film, overwriting is possible by changing either light intensity or pulse width.[24] They confirmed that when light intensity is fixed at 8 mW with no ferroelectric liquid crystal light bulb applied, irradiation of an 80 ns pulse erases the domain where recording is done using a pulse width of 250 ns. A pit forming model based on the magnetic bubble principle is used to understand this phenomenon. The rising temperature distribution when a small pit is to be recorded by using light intensity or a pulse with a small pulse width makes a domain wall energy curve,[25] which provides stress in the direction erasing the pit. In this case, pit erasure occurs, including an already recorded region[24] as shown in Figure 4.3.1.10. When light intensity and the pulse width are large, a large pit is formed and no erasure occurs. In this system, the floating magnetic field size at the time of recording is controlled by using a composition whose compensation temperature is between room temperature and the Curie temperature.

Y. Suzuki, et al., reported that erasure occurs even if a pulse is long.[26] They confirmed that when recording at light intensity of 17 mW and applied magnetic field of 30 Oe using 200 nm TbFeCo single-layer film (compensation temperature: 100°C, Curie temperature: 240°C), recording is done when irradiation is made at a pulse width of up to around 600 ns, whereas erasure occurs when the pulse width is 300 ns or more than 1 μs. Figure 4.3.1.11 shows overwriting characteristics for different magnetic fields and pulse widths. A is the recording domain, B the short-pulse erasure domain and C the long-pulse erasure domain. This may be explained by using a pit forming model, but it may be necessary to estimate the domain wall traveling speed against the cooling speed at the time of pulse irradiation.

(c) Other Materials for Light Modulation Overwriting Recording

A new method which uses exchange coupling film and achieves overwriting without an initializing magnet has been devised.[27] It uses exchange coupling two-layer film consisting of a memory layer and a reference layer, and recording domains are formed in the reference layer beforehand (preformat) and the transition metal spin within the reference layer's recording domains and that in the memory layer's unrecorded region are arranged in parallel. Recording and erasing are done in the memory layer. A laser beam warms the memory layer to the Curie temperature and the radius of the pit written becomes larger than the reference layer pit. As the two layers' spin directions are aligned in a region outside the reference layer pit, exchange energy becomes smaller, hindering shrinking of the memory layer's recorded pit in the cooling process. As a result, the pit remains in the memory layer, achieving recording. Conversely, when the radius of the written pit is smaller than the reference layer pit, the two layers' spin directions are aligned in a region outside the memory layer pit, encouraging shrinking of the memory layer recorded pit, achieving erasure. Figure 4.3.1.12 shows exchange energy "force" that works on the recorded pit of the memory layer at the time of recording/erasure. Domain wall moves and others are estimated by calculations, showing the possibility of overwriting.

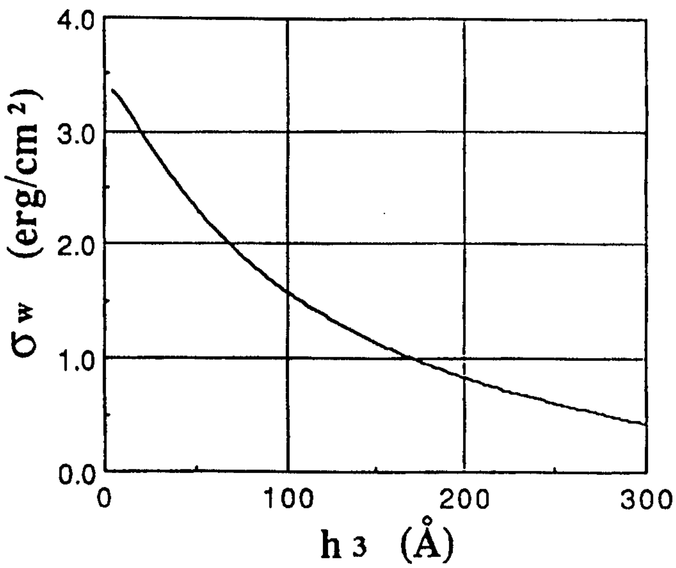

Figure 4.3.1.9. Change of Exchange Coupling Force in Accordance With Intermediate Film Thickness (By M. Kaneko, et al.,[23])

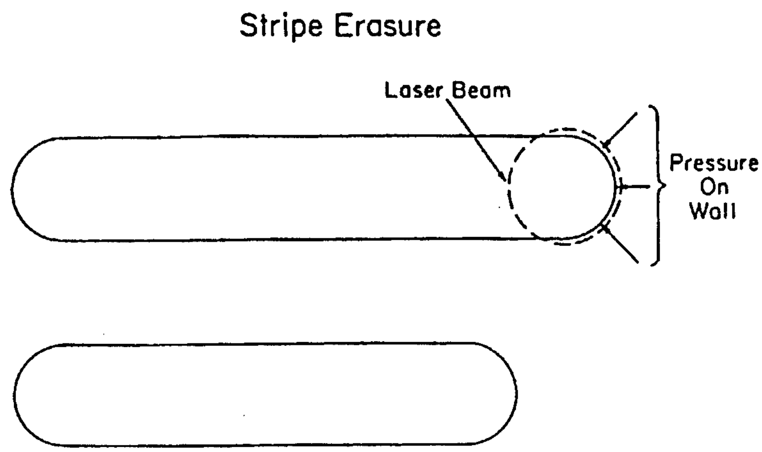

Figure 4.3.1.10. Principle of Pit Erasure in Single-Layer Film Overwriting (By M.H. Kryder, et al.[24])

There is also an idea to achieve overwriting, using a soft magnetic film's magnetic shielding effect.[28] As shown in Figure 4.3.1.13, the soft magnetic film (control layer) and permanent magnet film are laminated on the magneto-optic film (storage layer) and dielectric film (intermediate layer). When a

laser beam is irradiated, the soft film's temperature rises and the magnetic field working on the magneto-optic film changes. Overwriting is done by utilizing this phenomenon. Calculations show that overwriting is possible, though no experiment has been carried out.

(3) Trend of Development of Other Magneto-Optic Recording Materials

(a) High C/N Magneto-Optic Materials

There is a move to seek high C/N characteristics in order to record analog motion picture information. It is reported that an attempt was made to improve signals, using a disk laminating read film made of GdFeco, which has a large Kerr angle, and TbFe with good recording characteristics.[29] T. Yoshikawa, et al., tried to improve C/N form an overall viewpoint of media manufacturing, using Tb(Fe_{90XCo}10) single-layer film.[30] They measured, using a scanning tunnel microscope (STM), the roughness of the surface of a 30 cm-diameter glass substrate made by the 2P method, and demonstrated that the roughness greatly affects the noise level at the time of playback (Figure 4.3.1.14). They also obtained completely amorphous transparent dielectric film for overwriting enhancement by appropriately selecting film deposition conditions, resulting in C/N improvement of up to 5 dB. They achieved C/N as high as 65 dB by recording a 1 MHz signal on the disk's innermost track (diameter: 60 mm) at a disk revolution of 1,800 revolutions per minute (rpm).

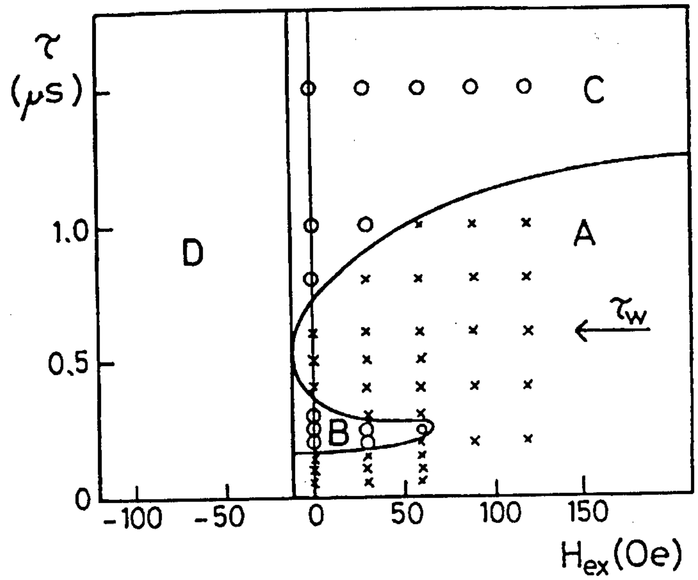

Figure 4.3.1.11. Overwriting Characteristics as Against Single-Layer Film Pulse Width (By Y. Suzuki, et al.[26])

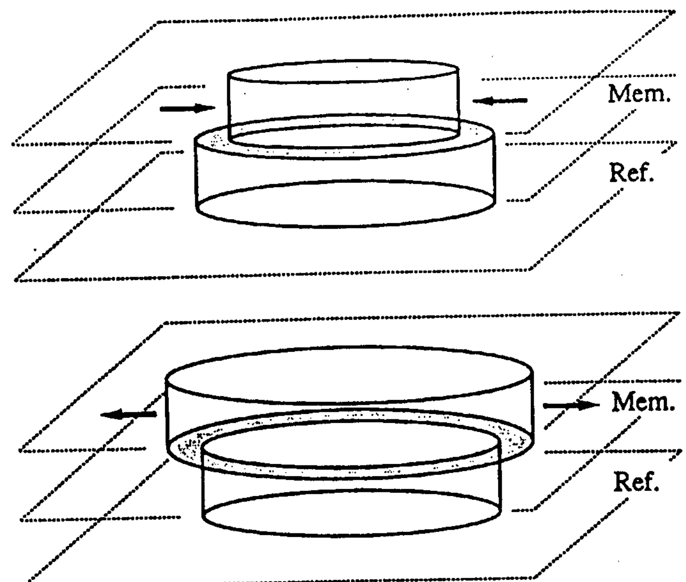

Figure 4.3.1.12. New Light Modulation Overwriting I (By Mathew D. Watson, et al.[27])

(b) Magneto-Optic Materials for Short-Wavelength Recording

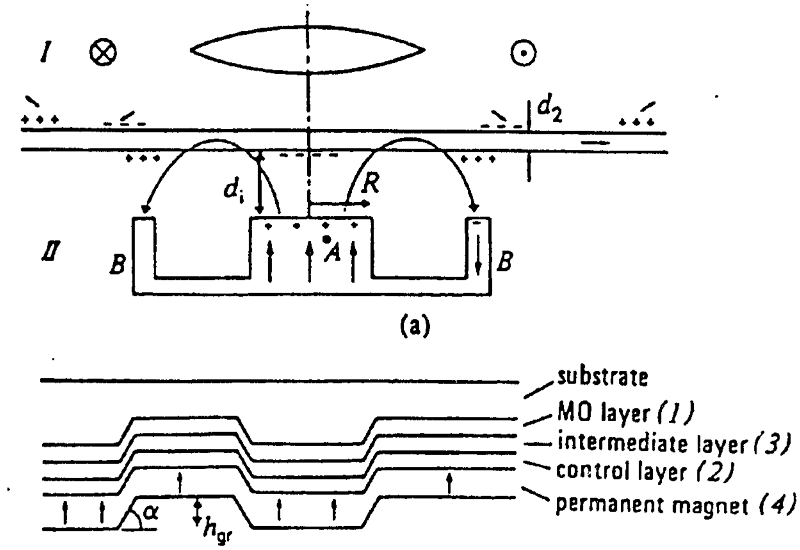

Figure 4.3.1.13. New Light Modulation Overwriting II (By H.A.M. Van den Berg, et al.[28])

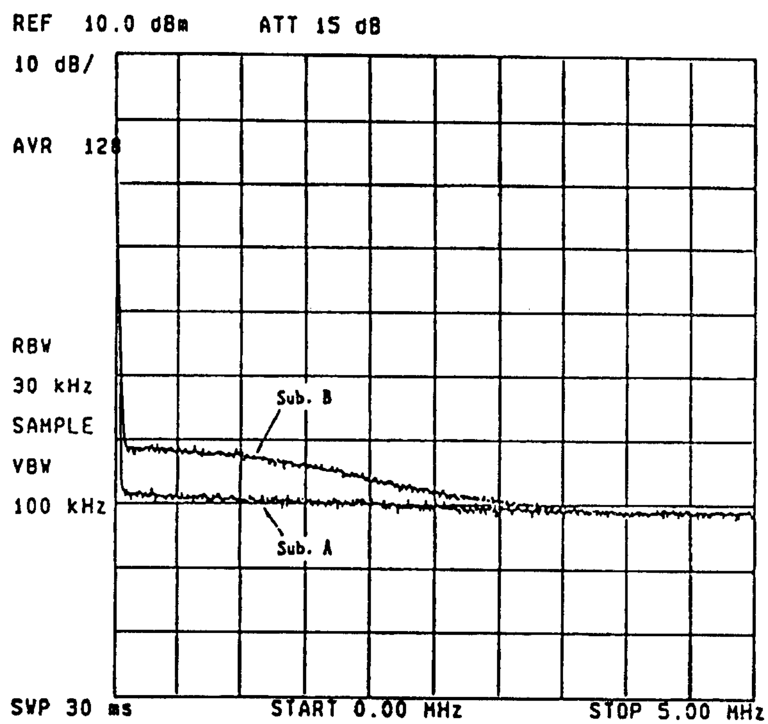

Figure 4.3.1.14. Disk Surface Roughness and Noise Level (By T. Yoshikawa, et al.[30])

Amid expectations for higher density of magneto-optic disks, magneto-optic materials suitable for recording using blue, green, and other short-wavelength light sources are gradually attracting attention. Two kinds of magneto-optic materials for short-wavelength recording have been reported so far—PtCo, PdCo, and other rare metals[31,32] and Nd and other light rare earth transition metal thin films.[33,34] As an example, wavelength dependence of $\sqrt{R} \times \theta_k$ of PtCo and PdCo is shown in Figure 4.3.1.15 in comparison with TbFeCo.[31] It shows that the performance index is improved remarkably in the short-wavelength region (400-–500 nm). However, these materials have a common disadvantage that their coercive force is small. Therefore, improvement measures, such as 1) the addition of heavy rare earth elements, and 2) the adoption of a two-layer structure, are under consideration. Takahashi, et al., carried out and observed 0.3 μm micro-domain recording using PtCo/TbFeCo two-layer film.[32] They demonstrated that a good selection of PtCo composition can improve recording characteristics.

In line with the advance of SHG and other optical technologies, new magneto-optic materials will be developed in the future. (Nakaoki)

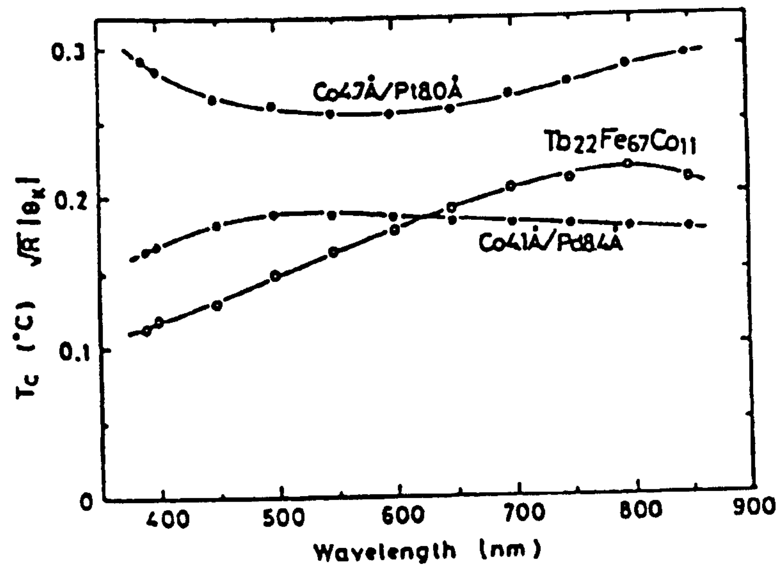

Figure 4.3.1.15. Dependence on Wavelength of Kerr Angle of Co/Pt, Co/Pd (By Hashimoto, et al.[31])

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Developments in PHB Recording Materials

926C1015R Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 546–554

[Text] **(2) Development Trend of PHB Recording Materials**

Tables 4.3.4.1 (organic materials) and 4.3.4.2 (inorganic materials) show photochemical hole burning (PHB) materials found so far, classified by reaction mechanism. As reaction mechanisms of organic materials are determined by kinds of guest, Table 4.3.4.1 does not include host compounds and shows only typical guest compounds (mostly there is no special restriction on organic material hosts as long as they are transparent and can diffuse guests uniformly). On the other hand, in the case of inorganic materials, guests and hosts often cannot be separated clearly. Thus Table 4.3.4.3 includes both.

Table 4.3.4.1. Reaction Mechanisms of Organic Guests

Reaction mechanisms	Typical compounds	Documents
Optical tautomerism	Phthalocyanine Porphin Chlorine	31 9, 10 32
Recombination of hydrogen coupling		5, 11
Optical decomposition	Tetrazene	12, 13
Optical dissociation	Adducts of anthracene and tetracene	14
Two-photon electron transfer reaction	Zinc-benzoporphyrin	15, 16
Cis-trans isomerization	Octatetraene	17
Optophysic process	Rhodamine 640 Cresyl violet	18 19

Table 4.3.4.2. Reaction Mechanisms of Inorganic Materials

Reaction mechanisms	Typical materials	Documents
Electron discharge	$Sm^{2+}:SrF_2$ $Sm^{2+}:BaClF$ $Sm^{2+}:BaCl_{0.5}Br_{0.5}F$ Color center in NaF Color center in LiF Color center of sapphire	20 21 22 23 24 25
Lattice distortion	$Cm^{4+}:CeF_4$	26
Relaxation to quasi-stable hyperfine level	$Eu^{3+}:Y_2O_3$	27

Characteristics of materials belonging to various reaction mechanisms are explained below.

(a) Organic Materials

Among organic materials, guest and host combinations are fairly free. Excluding special cases, materials which can molecule-diffuse guests can be used as hosts. Well-used host materials include highly transparent high-molecular materials like polymethyl methacrylate (PMMA), crystalline materials made by cooling and solidifying octane and other aliphatic hydrocarbons, and noncrystalline materials made by cooling and solidifying a methanol-ethanol mixture.

Performance benchmarks of PHB materials include multiplicity and hole burning speeds. These heavily depend on hole burning temperatures, laser intensity, and laser width, and it is difficult at present to compare values peculiar to materials. Therefore, this section will only qualitatively explain reaction mechanism-wise characteristics.

(i) Optical Tautomerism

Figure 4.3.4.3 shows optical tautomeric reaction, taking porphin as an example. With irradiation of light, the two N-H couplings at the center of a molecule are broken and hydrogen atoms couple with adjacent nitrogen atoms. The quantum yield rate of the reaction is around 1 percent, but as the optical reaction occurs at the center of the guest molecule, the host cannot affect the reaction itself and thus the yield rate does not change greatly even when the host is changed.

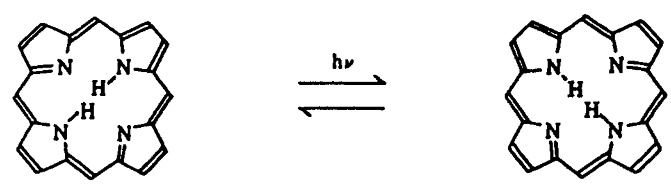

Figure 4.3.4.3. Optical Tautomerism of Porphin

Similarly, it is possible to introduce various substitution radicals without harming reactivity, and PHB has been observed in many derivatives. It has been generally said that the PHB phenomenon occurs only at a cryogenic temperature of around liquid helium temperature, but it was observed at liquid nitrogen temperature (77 K) for the first time with the use of a porphin derivative.

Figure 4.3.4.4 shows the structural formula of the porphin derivative which showed PHB at the liquid nitrogen temperature.[9] Polyvinyl alcohol (PVA) was used as the host. The visible absorption spectra of these materials are similar. As an example, the absorption spectrum of a specimen in which TSPP (Na) is diffused is shown in Figure 4.3.4.5. The hole was made by a pigment laser in the absorption band with the maximum value at the wavelength of 640 nm. The relationships between the hole burning temperature (T) and the half-width (Γ) of the hole made of TSPP (Na)/PVA and TCPP (Na)/PVA are shown in Figure 4.3.4.6. With either specimen, it was possible to burn a hole at a temperature above liquid nitrogen temperature. Measurement results are generally similar for other compounds.

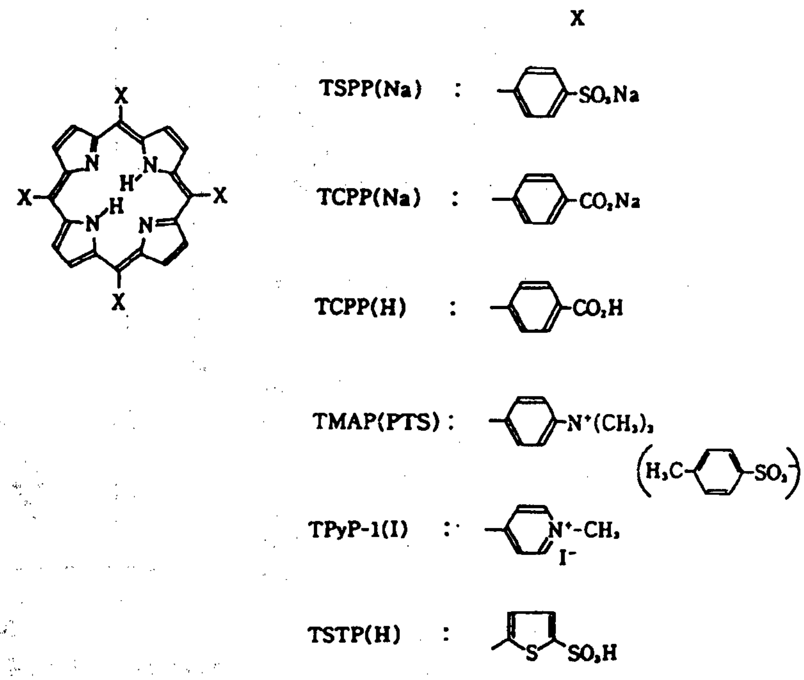

Figure 4.3.4.4. Ion Porphin Derivatives (By K. Sakoda, et al.[9])

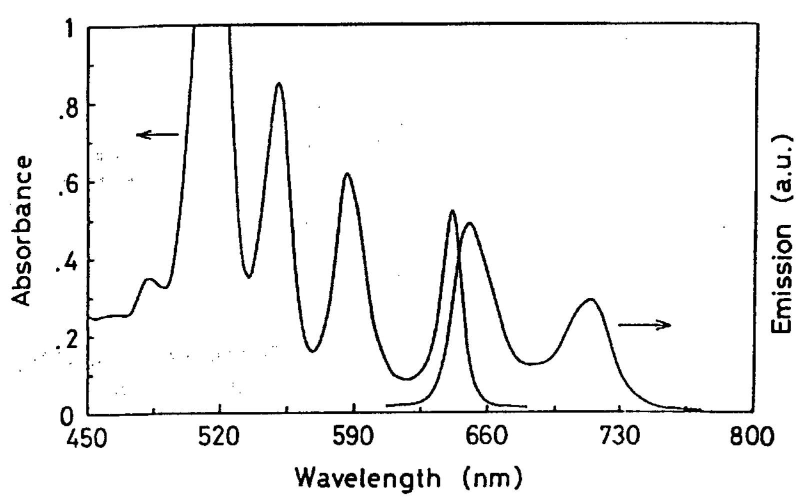

Figure 4.3.4.5. Absorption and Emission Spectra of TSPP (Na)/PVA (By K. Sakoda, et al.[9])

As is evident from Figure 4.3.4.6, the hole half-width depends on temperature and they have the following relationship:

$$\Gamma \propto T^a \qquad a \sim 1.7$$

Multiplicity calculated from the measured value of Γ is around 2,000 at liquid helium temperature and around 10 at liquid nitrogen temperature.

Horie, et al., of the University of Tokyo, found that it is possible to burn a hole at a temperature above liquid nitrogen temperature with a material in which tetraphenylporphine (TPP) is diffused in phenoxy resin.[10]

(ii) Hydrogen Coupling's Recombination Reaction

Figure 4.3.4.7 shows the reaction of (kinizarin) (also called DAQ). In this reaction, the hydrogen coupling within the kinizarin molecule is broken, creating hydrogen coupling between kinizarin and the host. Therefore, unlike in optical tautomerism, the quantum yield rate is greatly affected by the host.[11] Particularly, no hole is made in a host with no capability of hydrogen coupling. The maximum value of the quantum yield rate is in the order of 0.01 percent. Compared with optical tautomerism, thermal reverse reaction tends to progress and a temperature rise tends to erase a hole.

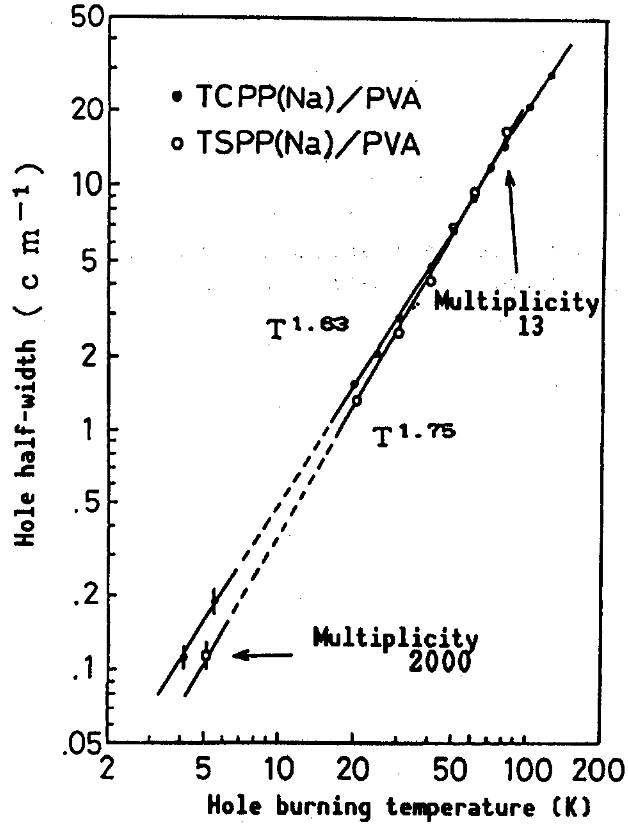

Figure 4.3.4.6. Relationship Between Hole Half-Width and Temperature (By K. Sakoda, et al.[9])

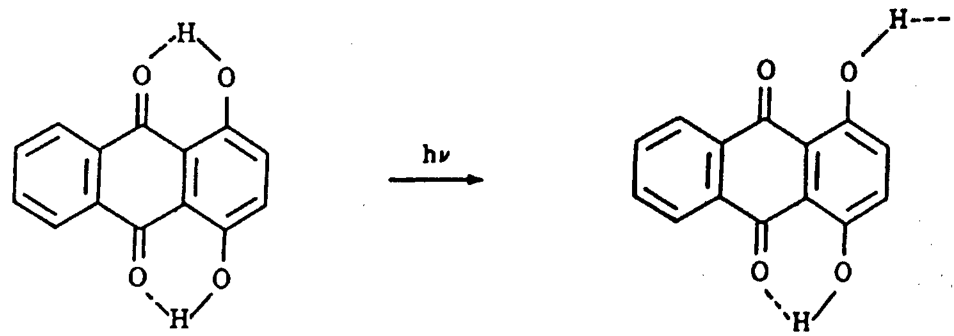

Figure 4.3.4.7. Hydrogen Coupling Recombination in Kinizarin

(iii) Optical Decomposition

Literally, guest molecules decomposed as they absorb a laser beam. Typical examples are tetrazene and dimethyl tetrazene,12,13 but studies are fewer than those on porphin and kinizarin.

(iv) Optical Dissociation

Optical adducts like anthracene-tetracene show this reaction, which is said to be a two-photon reaction.[14] Only a few studies have been made on this.

(v) Two-Photon Electron Transfer Reaction

Materials known to show this reaction are those whose electron donor is a zinc-tetrabenzoporphyrin derivative and electron acceptor is chloroform.[15,16] A hole is burned on these materials usually by irradiating two laser beams with different frequencies (wavelengths) simultaneously. As shown in Figure 4.3.4.8, guest molecules relax into the triplet state by absorbing the first laser beam. With the absorption of the second laser beam (called gate beam), electrons fly from the electron donor to the electron acceptor.

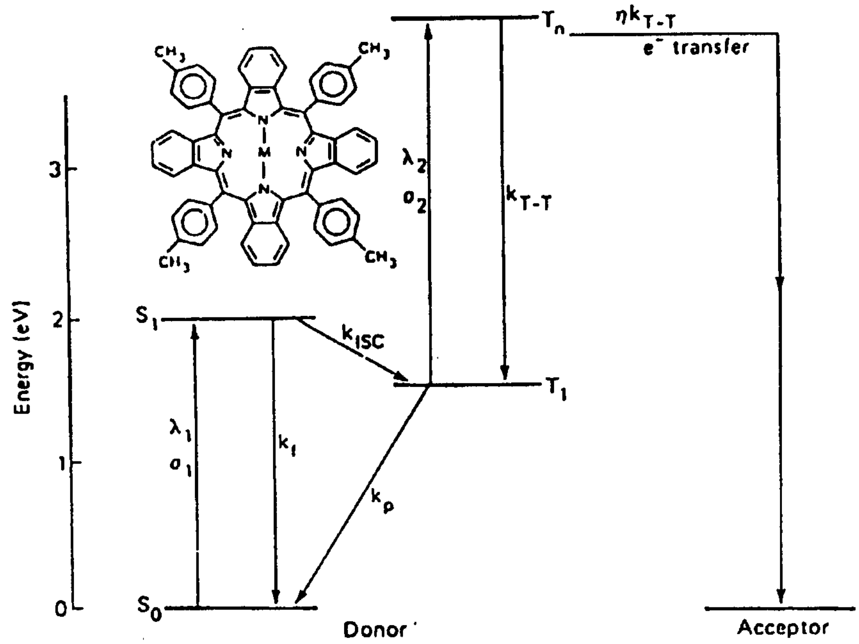

Figure 4.3.4.8. Two-Photon Electron Transfer Reaction of Tetrabenzoporphyrin Derivative (By T.P. Carter, et al.[15])

The largest advantage of the two-photon reaction is that no reaction occurs when the gate beam is not irradiated. The single-photon reaction has a problem called "destructive read," a reaction that gradually progresses by light irradiated in order to play back recorded data. On the other hand, no gate beam is irradiated for playback in the two-photon reaction, solving this problem. The irradiation of a high-intensity laser beam is required to make a hole at high speed, but absorption saturation is reached easily in the single photon reaction and the success rate of hole burning decreases as intensity increases. However, saturation has little influence in the two-photon reaction, making it suitable for high-speed recording.

(vi) Cis-Trans Optical Isomerization

Guests known to have this mechanism include octatetraene[17] but only a few studies have been made.

(vii) Optophysic Process

Materials falling under this category include rhodamine 640 and other xanthene pigments and oxadin pigments like resorphin and cresyl violet.[18,19] In this mechanism, actually no optochemical reaction is considered to take place. A hole is burned nonetheless because the three-dimensional structure of the host around the guest molecule is changed by energy released when the guest molecule in the excited state after absorbing the laser beam returns to the basic state, and the position of the guest's absorption band changes as a counter-reaction. The quantum yield rate of the reaction is generally low in the order of 0.01 percent at the largest. The host's three-dimensional structure generated around the guest molecule is easily disturbed thermally and a rise in temperature tends to erase a hole.

(b) Inorganic Materials

Reaction mechanisms peculiar to inorganic materials are mainly the following three. Others include the optophysical process of Pr^{3+} and Nd^{3+} ions introduced into silica glass.

(i) Electron Discharge

Ion crystals having Sm^{2+},[20-22] and color centers in an alkaline halide[23-24] react under this mechanism.

Sm atoms originally are stabilized in the three-value state, but can exist stably in the two-value state if the host crystal is selected well. Figure 4.3.4.9 shows the energy level of Sm^{2+} ion in a BaClF crystal. Electrons are discharged by two-photon absorption and Sm^{2+} becomes Sm^{3+}. In this specimen, thermal reverse reaction is very small. It has a remarkable feature that, as the host is crystalline, the hole generated can be maintained at room temperature. Actually, Winnacker, et al., reported that holes with half-width of 100--250 MHz burned at 2 K can be observed clearly when they are preserved at room temperature for several days and then temperature is lowered to 2 K again.[21] Wei, et al., reported that when a BaClF-BaBrF mixed crystal is used as the host, heterogeneous width widens and a hole can be burned even at liquid nitrogen temperature.[22] However, the oscillator strength of electron transitions such as from $^7F_0$ to $^5D_0$ of Sm^{2+} ions used for PHB reaction is small, working as a hurdle to practical use.

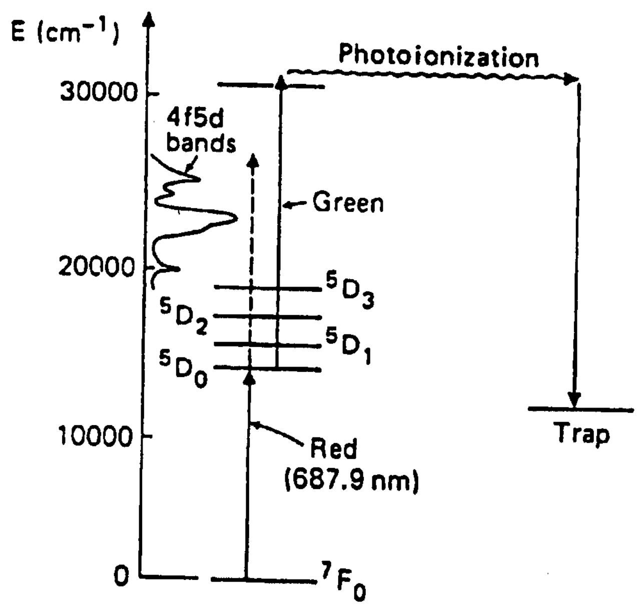

Figure 4.3.4.9. Two-Photon Electron Discharge Reaction of Sm^{2+} Ion (By A. Winnacker, et al.[21])

Meanwhile, PHB is observed by the electron discharge reaction of various color centers. Of them, the color center of NaF has relatively high hole-burning quantum yield of 1 percent.[23] As for the color center of sapphire, a hole burned at 5 K can be observed when the temperature is raised to room temperature and then lowered again to 5 K.[25]

(ii) Lattice Distortion

Liu, et al., of the Argonne national institute found that optical excitation of Cm^{4+} ions introduced into a CeF_4 crystal for doping causes lattice distortion, changing the absorption band of Cm^{4+}. They reported that when a laser beam is irradiated to the new absorption band thus generated, the lattice distortion disappears and a hole is generated. At temperatures above 45 K, lattice distortion is unstable.

(iii) Relaxation to Quasi-Stable Hyperfine Level

The $^7F_0$ basic state of the Eu^{3+} ion is divided into three sublevels by the hyperfine mutual reaction. Optically excited electrons return to the basic state after releasing energy, but they do not necessarily return to their original sublevels. Thus, the absorption spectrum is different before and after optical excitation and a hole is burned. For example, hole burning in Eu^{3+}:Y_2O_3 under this mechanism was reported.[27] In this example, it takes about 30 hours for a sublevel to relax and return to the state of thermal equilibrium, relatively long among materials of this kind.

(3) Recording and Reproduction Technology Trend

In order to commercialize PHB high-density recording, it is necessary to develop not only high-performance materials but also recording and reproduction technology. Particularly, high-speed recording and reproducing technology is indispensable. Hole burning and detecting equipment using a pigment laser of spectroscope used in labs is not suited to this purpose. This section outlines recording and reproduction technology tried so far for high-density recording.

(a) High-Speed Reproduction With Semiconductor Laser

Hole detection using semiconductor laser frequency sweep by injection current adjustment was reported.[28,29] Nakatsuka, et al., modulated the oscillation frequency of a single-mode semiconductor laser at around 2.5 GHz/ms and detected a hole in PVa doped with cyanine pigments.[28] Their original intention was to track a hole's shape changes on a real-time basis, but succeeded in reading the hole up to 1,000 times repeatedly during that process. Meanwhile, Shellenberg, et al., studied hole reading at a modulation speed 1,000 times faster (3 THz/ms).[29] They reported a transfer speed of about 20 Mbits/s is possible.

(b) Real-Time Reproduction Using Induced Photon Echo

As explained earlier, time–domain recording and reproduction become possible by combining PHB materials and induced photon echo. The pulse light time width that can be recorded is determined by the length of the guest's phase relaxation time (T_2), T_2 of organic pigments in polymers is in the order of nanoseconds at best, whereas that of rare earth ions in a crystal is in the order of microseconds. Therefore, recording and reproduction are possible with conventional electronic technology for the latter. For example, Mitsunaga, et al., generated 248–bit echo signals with a good signal to noise ratio (S/N) ratio using $Eu^{3+}:YalO_3$ as the medium.[7] Real–time recording and reproduction using conventional electronic technology are difficult for media with short T_2, such as organic pigments in polymers. However, it is proved that recording and reproduction are theoretically possible by using a quantum electronic method.

(c) Multiple Holography

It is possible to make multiple holograms within PHB materials by using a variable–frequency laser. Recording and reproduction can be done like conventional holography[30] and the induced photon echo method explained in the previous section can also be used.[8] For example, Wild, et al., of the Swiss Federal Institute of Technology (ETH) reported on the former.[30] They made multiple holograms, using multiple laser frequencies, in polyvinyl butyral in which oxadin–based pigments are scattered and multiple holograms in one medium, using the Stark effect accompanying electric field application explained at the end of (1)(b).

In a recording method like holography where information is handled in parallel, there is no need to form a microspot of laser beam on a PHB medium. In contrast, recording with microspots as in conventional optical disks requires technology to condense a laser beam on a medium placed in a cryostat filled with liquid helium or liquid nitrogen. As it is difficult to place a condenser lens close to the medium, the spot size, which is determined by diffraction limitation, becomes larger than that of conventional optical disks, resulting in a drop in recording density.

(d) Making Microspots in Cryostat

It is difficult to make microspots in a cryostat, but several attempts have been made. In detecting a hole using a semiconductor laser explained in (3)(a), Shellenberg, et al., condensed a laser beam on a PHB medium placed in a cryostat and, at the same time, made multiple holes at different places on the medium by sweeping the beam using a galvanomirror.[29] The spot diameter was 12 μm, which is apparently the smallest so far reported.

Expectations of New Materials, New Technologies

926C1015S Tokyo HIKARI GIJUTSU DOKO CHOSA HOKOKUSHO VII in Japanese Mar 91 pp 558-563

[Text] **In Expectation of New Materials and New Technologies**

As 4.3 already pointed to some materials and technologies which we will see in the future, there will be need to repeat here. Table 4.4.1.1[1] [not reproduced] classifies optical recording from the viewpoint of principles. Expectations for new materials and technologies stem from a detailed analysis of this table.

The noninterference/spatial type includes compact disks (CDs) now used, magneto-optic materials described in 4.3.1, phase-change inorganic materials explained in 4.3.2, and photochromic materials in 4.3.3 Within a laser spot focused on a recording medium, one bit of information is written by thermal change, magneto-optic effect, phase change, and light absorption change. These materials range widely from those already made into devices to those whose material selection is entering a final phase at last. When seen from the current optical recording systems, they can provide device systems that can most easily replace existing magnetic recording materials. Thus the important problem of research is how to secure good specifications of materials among device systems very similar to magnetic recording.

As for the interference/spatial type, holography already exists as a technically established recording method. As the current survey picked up only materials that lead to digital recording, it did not mention hologram generating materials. This field requires massive research and development and should be studied and analyzed in detail elsewhere. Photochromic materials covered by the current survey are interesting as hologram generating materials. Although this report does not discuss holography much, we want to emphasize that it is a classification item indispensable to image processing and parallel information processing utilizing the wave characteristics and interference of light.

PHB materials explained in 4.3.4 fall under the noninterference/frequency category. As PHB materials allow writing information in the frequency domain, it theoretically becomes possible to write more than 1,000 multiples of

information in one laser spot if a suitable read/write method is found. Actually, as explained in 4.3.4, this is possible in a domain close to liquid helium temperature and researchers are seeking a medium that causes no drop in multiplicity in a higher temperature range. There are several other cases where this proves effective.

One case is that frequency-domain multiplicity is brought into a noninterference/spatial system like CDs and multiple information is added to a laser spot which usually holds only one bit of information. A similar idea is to write multiple images on a single PHB material having two-dimensional expanse using frequency multiplexing, and carry out an operation between images by combining them. Considering the fact that the use of the parallel processing capability of light is theoretically superior to electronic processing, the future of PHB materials lies in developing these technologies. PHB materials are single-thin film materials and can also be used as frequency filters having a very narrow bandwidth against multiple frequencies. As rewriting is possible, they are far superior to existing spectroscopes and multilayer film filters in terms of compactness and simplicity. Used in combination with holography technology, PHB materials enable frequency-multiplexing holography. They have proved to be able to process well three-prime color holography and motion picture holography,[2] which are very difficult, if not impossible, for other media.

The last category is interference/frequency photon echo. The principle and read/write of photon echo memory are already explained in 4.3.4. The interesting point is that information written in a certain time series can be retrieved one after another as optical output with a corresponding time series or special correlation. In the three other types, timing is controlled by instructing with a pulsed write beam or read beam from an outer system or by scanning the access point on the recording medium. In photon echo memory, the medium itself has a time series in memory and thus it has the possibility of leading to a totally new optical information processing technology.

It is interesting that frequency-type materials, either noninterference or interference, can be used in such a way as to compound their characteristics with those of spatial-type materials in processing them into devices, as explained earlier in relation to PHB materials. This is in contrast with the fact that materials that are excellent as spatial-type materials and at the same time have features of frequency-type materials have not yet been found. However, hole burning is the only phenomenon that can be used among frequency-type phenomena and materials which can realize this phenomenon have many problems to be solved before being put to practical use.

Problems involved in PHB materials are explained in 4.3.4. Photon echo memory has similar restrictions[1] because it uses the same phenomena. For example, organic pigment-based PHB materials are the best in terms of long recording, but they require cryogenic temperatures or very short optical pulse technology for read and write and it is too early to consider putting them to practical use. Rare earth ions in a crystal are easy to study for memory of this kind. Recording time is limited and they also require cryogenic temperatures, but recording density can be increased and relatively easy-to-use optical pulse technology can be used. In my personal view, recording density will be more

important than memory retention time for high-speed optical parallel processing using a transient memory. Anyway, research in this field has just started and has yet to reach a point where detailed analysis of materials can begin. Being frequency types, PHB materials have features of both the noninterference and interference types. Thus, processing methods in which both exist should also be considered.

The fusion of various advanced technologies tends to give birth to further advanced technologies. Such a trend is gradually seen in the optical recording sector. Some examples are noted below.

Fujishima, et al.,[3] developed a new information recording method, combining light and electrochemistry. Under the method, the three types of azobenzene and other compounds, as shown in Figure 4.4.1.1, are controlled by light and electricity. It is marked by reading with light without destroying the record. They estimate that the use of a scanning tunnel microscope (STM) in electrochemical operation will allow recording of 10^{12} bits/cm^2. Apart from the possibility of realization, this method is significant and trail-blazing in that it shows contact between optical memory and STM in a specific example.

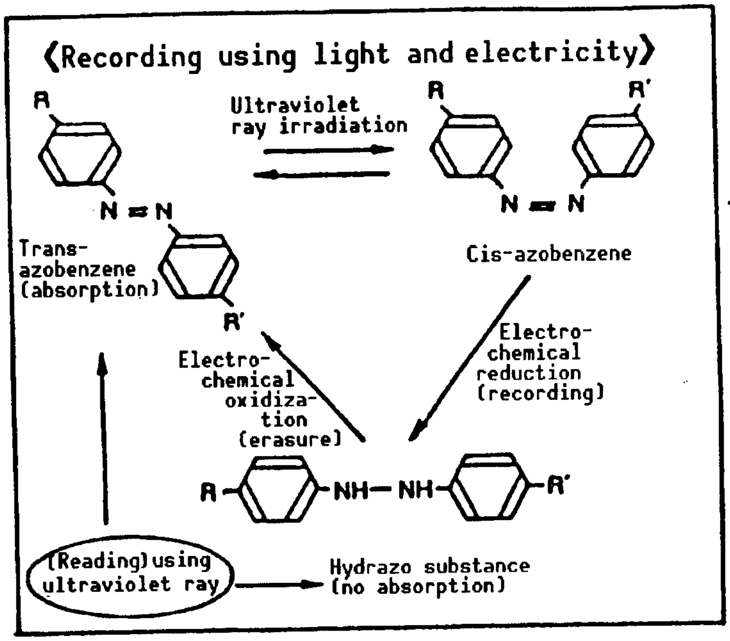

Figure 4.4.1.1. New Information Recording System Combining Light and Electrochemistry (By Fujishima, et al.[3])

High molecules are also used in materials taken up in 4.3 of this survey, but strictly as the host of optically activating substances. But the host itself may change its nature due to light and become usable for information recording. Suited for this possibility are liquid crystals and high molecules. Among recording materials using high molecules as media, photopolymers and organic photoconductors (OPCs) were put to practical use a fairly long time ago. These materials were made for microprocessing resists and image recording, but several attempts have started to develop them into digital memory.[4] Coating film deposition on high molecules is easy and they are promising as recording materials capable of nonprocessing or dry processing. From this viewpoint, subject to research are various types of materials, such as those using high-molecule phase transition caused by light or heat, a change in phase solubility of low molecular-weight substances scattered in high molecules, or a change in refraction or light diffusion stemming from a phase change. But a few can be put to practical use in view of recording speed, resolution, and CN ratio, and it is necessary to improve the performance of materials based on analysis of recording mechanisms.

As explained in detail in Chapter 4, "Nonlinear Optical Materials and Applications," of the previous fiscal year's survey report, investment in research on nonlinear optical materials has been soaring sharply year after year.[5,6] Nonlinear optical materials and optical recording materials sometimes handle substances and phenomena similar in many points. It thus seems not a dream to develop real hybrid materials having both memory and nonlinear effects in the future. There is, if small in number, research spearheading such development efforts. For example, research was conducted in which high-molecular matrix was doped with organic pigments having both optical recording capability and optical nonlinear response capability, and holographic long recording and transitional phase conjugate wave generation were done in the same medium.[7] The phase conjugate wave is a time-reversal reflection wave that is obtained by the light refraction effect or the use of materials having ternary nonlinear receptivity. The peculiar nature is expected to be applied to various new information processing technologies. Fujiwara, et al.,[7] demonstrated optical operation between holographically stored information and information held by the phase conjugate wave. This seems to predict the next generation of optical recording materials. Naturally, R&D of new optical recording materials needs to progress further in order to lead such attempts to success.

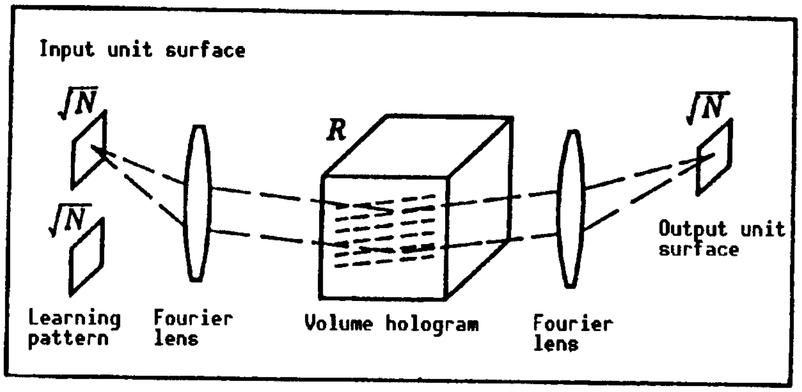

Figure 4.4.1.2. Basic Optical System of Optical Neural Network Using Volume Hologram (By Kitayama, et al.[8])

Let us discuss neural networks as the last topic. An accurate explanation of a neural network is beyond the author's power. But it can be defined as a network consisting of numerous nonlinear response devices corresponding to neurons and capable of plastic coupling. It is expected to open the way for super-parallel computing with learning capability, which is difficult with conventional von Neumann computers. There is an optical neural network idea to build neural network hardware using optical technology. An optical neural network using spatial optical modulator is well known, but the use of earlier-explained phase conjugate wave generating mirrors and volume holograms is now under study.[8] Figure 4.4.1.2 shows an example in which, when a certain learning pattern is presented, input layer unit-output layer unit wiring is recorded as a Fourier hologram of reference light from the input surface and object light of the learning pattern. The recorded phase lattice is formed in such a way as to satisfy the Bragg diffraction conditions corresponding to the positional relationship of the two units and diffraction efficiency provides coupling weight. When the phase lattice is recorded multiply, many units can be coupled. It is thus possible to give neural network information to the optical recording medium, not simply recording one bit or one image on it, indicating that there theoretically exists very advanced use of materials—recording and information processing.

Combination of optical recording materials and new technologies is expected to give totally new functions to materials. I hope more research will be done in this field. (Moriya)

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4.5 Conclusion

We conducted a survey on optical recording materials needs and the development trend of new optical recording materials.

Considering needs of the system side, what people expect most from optical recording materials is apparently large capacity for computer digital data storage for the time being. Overwriting capability is indispensable in view of competition with magnetic memory. Needs of the audio-video sector have peculiar characteristics, but demand for optical recording materials will no doubt increase.

Among new materials, magneto-optic materials are already in the practical use stage and therefore it may be inappropriate to add "new." R&D efforts are focused on improvement of materials for better performance, selection of read/write methods and optimization. They are most advantageous in terms of compatibility with existing systems because technology involved is very

similar to magnetic memory technology as they also utilize their magnetic property.

Phase-change inorganic materials are coming close to commercialization. If they achieve better results than other materials in terms of manufacturing methods and durability, they are very promising because they can be used in systems similar to compact disks (CDs) and laser disks (LDs). The key to their practical use is how to capitalize on their overwriting capability.

As for photochromic materials, much research is still designed to seek efficient photochromic molecules and matrix materials capable of stable read/write. No definite conclusion has been reached on recording methods as they depend on materials. But being capable of holographic recording, they have new potential.

PHB materials are the sole materials that enable frequency-multiplex and time-multiplex recording, and fall under the so-called future materials category. but research is still in the basic stage because cryogenic temperatures are required for longer recording times and higher recording density and read/write technology itself is too advanced to put to practical use immediately. However, theoretical demonstrations of new information processing technologies have steadily been made and uses which can overcome many difficulties will be found in the not too distant future.

We want to conclude with the hope that new phenomena and new uses involving these new materials will be frequently found to spur their practical use. (Moriya)

\- END -

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